MAP Internal Charging Review

at

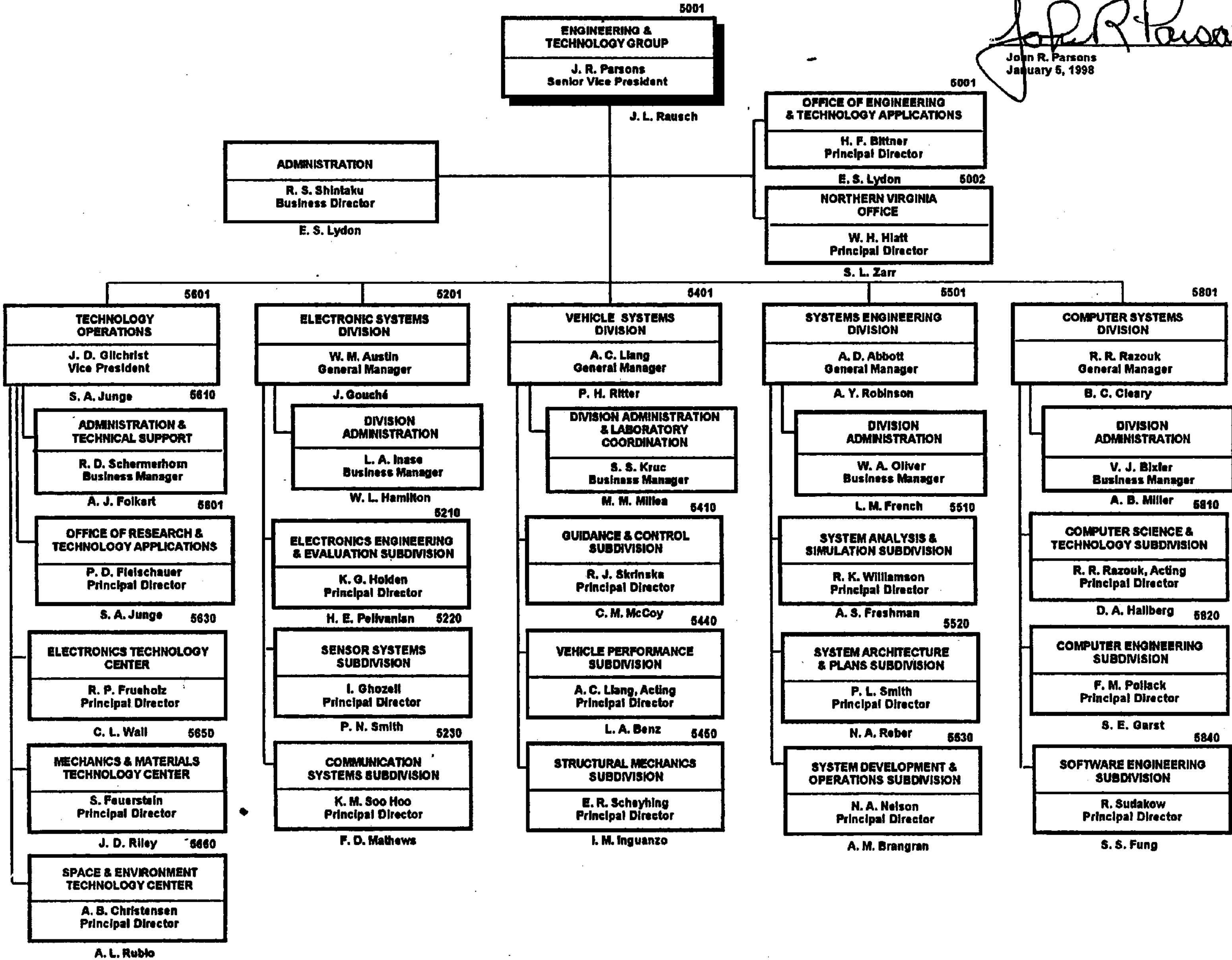
The Aerospace Corporation

8-9 September 1999

The Aerospace Corporation

- A California nonprofit corporation
- A Federally Funded Research and Development Center (FFRDC)
- Chartered to provide support to the U.S. Government in planning and acquisition of space and launch systems
- Employs ~3600 people, ~2300 technical staff (~25% PhD, ~40% MS)
- Works on all DoD boosters and space systems
- Principal tasks: systems planning, systems engineering, integration, and launch verification

John R. Parsons
January 5, 1998



Space and Environment Technology Center

Capabilities Outline

Space and Environment Technology Center

A.B. Christensen, Prin. Director
(310) 336-7084

Surveillance Technology	J. T. Knudtson, 336-8705
Remote Sensing	C. J. Rice, 336-1749
Space Sciences	J. B. Blake, 336-7078
Space Instrumentation	L. M. Friesen, 336-5992

Surveillance Technology Department

- Environmental Chemistry
- Molecular spectroscopy
- Toxic Plume Modeling
- Gas Phase Chemical Kinetics
- Effluent Monitoring
- IR Imaging and Spectroscopy
- Flight Sensor Development
- Optics
- Infrared Imaging

Space Sciences Department

- Energetic Space Radiation and Effects
- Space Plasma Physics
- Spacecraft Charging
- Upper Atmospheric Physics
- Ionospheric Physics
- Mathematical Analysis, Data Processing and Computer Programming
- X-Ray Detection in Space
- Solar Physics

Remote Sensing Department

- IR and Visible Remote Sensing
- Spectral Signatures
- Atmospheric Measurements
- Radiative Backgrounds
- Radiation Transport
- Celestial Sources and Backgrounds
- Sensor Performance
- Optical System Design and Calibration

Space Instrumentation Department

- Spaceflight Design and Development
- Instrument Construction
- Ground Experiment and Support Equipment
- Radiation Effects Testing
- Sensor Design and Test
- Computer Systems and Network Management
- Spaceflight Qualified Fabrication

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Space Sciences Department

Space Sciences Department
J.B. Blake, Director
(310) 336-7078

Energetic space radiation	J.F. Fennell, 336-7075
Single event upset	R. Koga, 336-6583
Space plasma physics	H.C. Koons, 336-6519
Space plasma theory	M.W. Chen, 336-8565
Upper atmosphere physics	R. L. Walterscheid, 336-7352
Applications programming	G.M. Boyd, 336-5990

Energetic Space Radiation

- Trapped radiation environment and dynamics
- Solar and galactic cosmic ray populations
- Artificial radiation belt dynamics
- Analysis of radiation effects on satellite components
  - Total dose/annealing effects
  - Single particle upset
  - Sensor backgrounds

Space Plasma Physics

- Spacecraft charging
  - Surface/buried dielectric effects
  - Discharge generated EMI
  - Surface degradation/contamination
- Wave particle effects
  - Ionospheric wave propagation
  - Ionospheric effects of particle precipitation
  - Radiation-belt flux limits
- Ionospheric effects and modification
  - Chemical releases
  - Ionospheric heaters

Upper Atmosphere Physics

- Dynamics
  - Global circulation
  - Energy, momentum sources
  - Auroral phenomena
  - Wave propagation
- Upper atmosphere structure and composition
- Modeling
  - Empirical models of density, temperature
  - Empirical ionospheric models
  - Theoretical models
- Upper atmosphere effects on space systems
  - Drag
  - Frictional heating

Applications Programming

- Analysis
  - Numerical analysis
  - Satellite ephemeris/attitude
- Modeling
  - Geomagnetic field
  - IR transmittance
  - Space radiation environment
- Computer programming
  - Scientific programming
  - Satellite data reduction
  - Graphic data displays
  - Interactive data analysis

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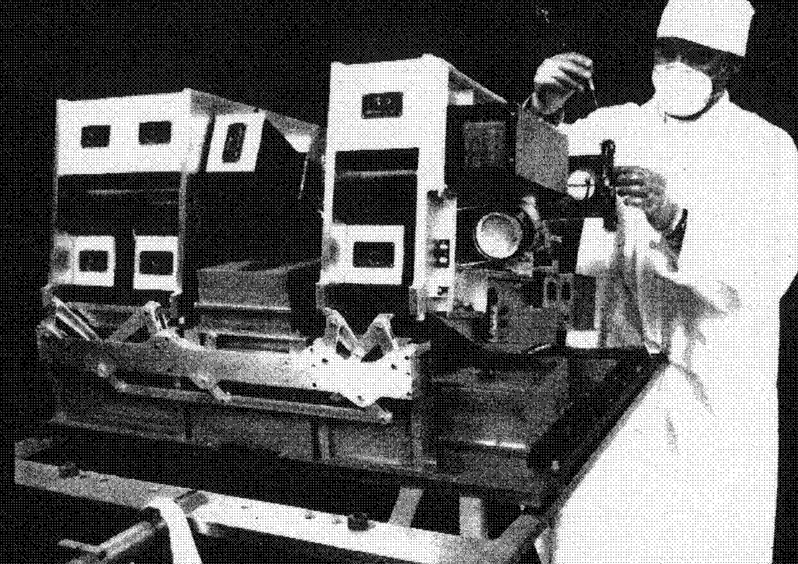
SETC
Space Weather Related Activities

- Research
- Design requirements and specifications
- Source selection
- Parts and materials testing
- Test specifications and analysis
- Design Reviews
- Independent Readiness Reviews
- Anomaly analysis
- Education

Space Instrumentation

Capabilities

- Fully staffed instrumentation department with engineers, technicians, facilities
  - Instrument design, fabrication, testing, launch operations, and data processing
  - Thermal vacuum test facilities, NASA-approved assembly facilities
  - Surface mount facility, vibration, etc.
  - 24 engineers, 5 support staff



Utilization

- Flight History
  - 33 years building space instruments
  - 186 flight experiments
  - 68 satellites
  - 25 sounding rocket flights
- Ground-based and airborne experience

Customers

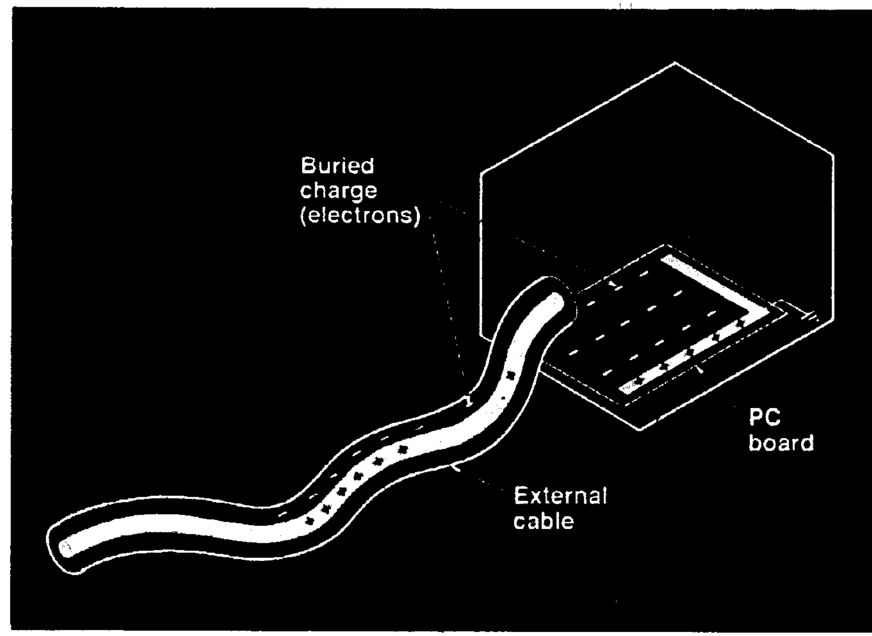
- NASA, NRO, DMSP, STP, commercial

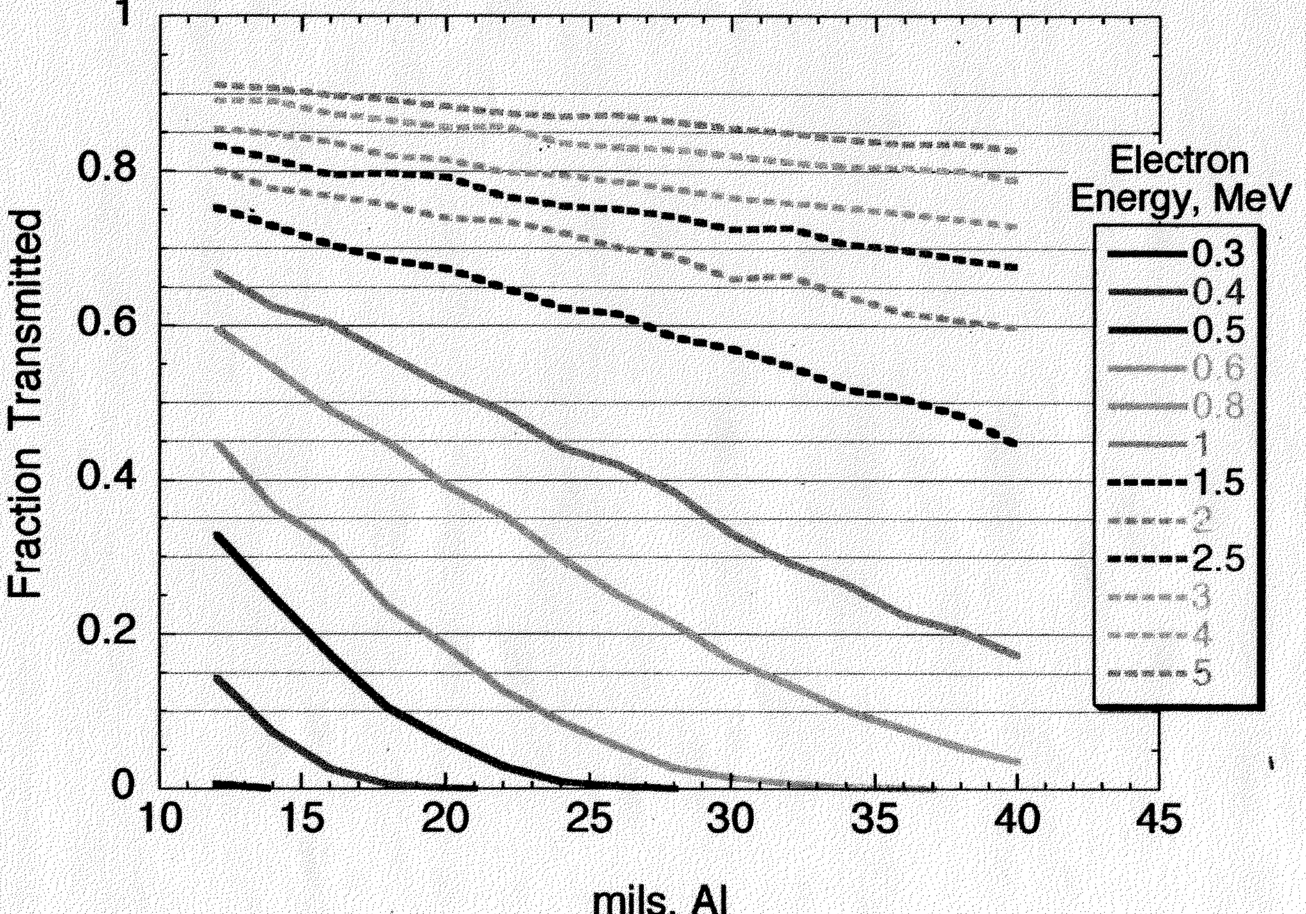
Overview of Internal Charging and Aerospace Analyses

- History of Internal Charging
  - Spacecraft Anomalies
  - Spacecraft Measurements
  - Laboratory ESD Tests
- Internal Charging Environment for MAP
- Comparison of Environment with AE8MAX
- Statistical Properties of CRRES MEA Measurements
- Simulation Results for MAP Cable
- Simulation Comparison for CRRES & MAP Cables
- Concept of a "Safe Limit" and "Zero Discharge Level"
- Recommendation

Internal Charging Locations

- Internal charging may occur at a variety of locations including:
  - dielectric isolators
  - dielectrics in cable harnesses
  - printed circuit boards
  - conformal coating
  - isolated conductors such as spot shields on ICs
  - interior paint



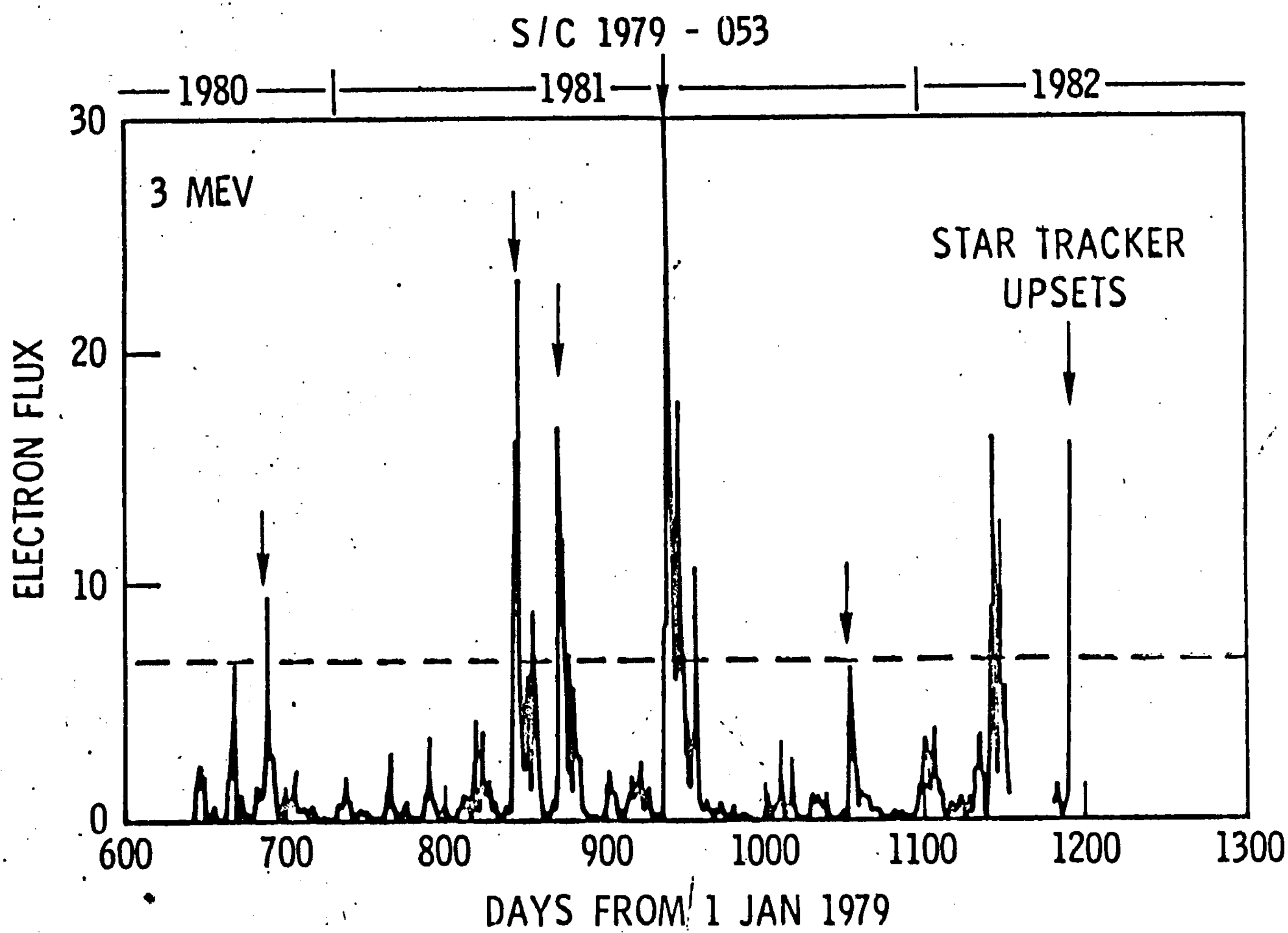


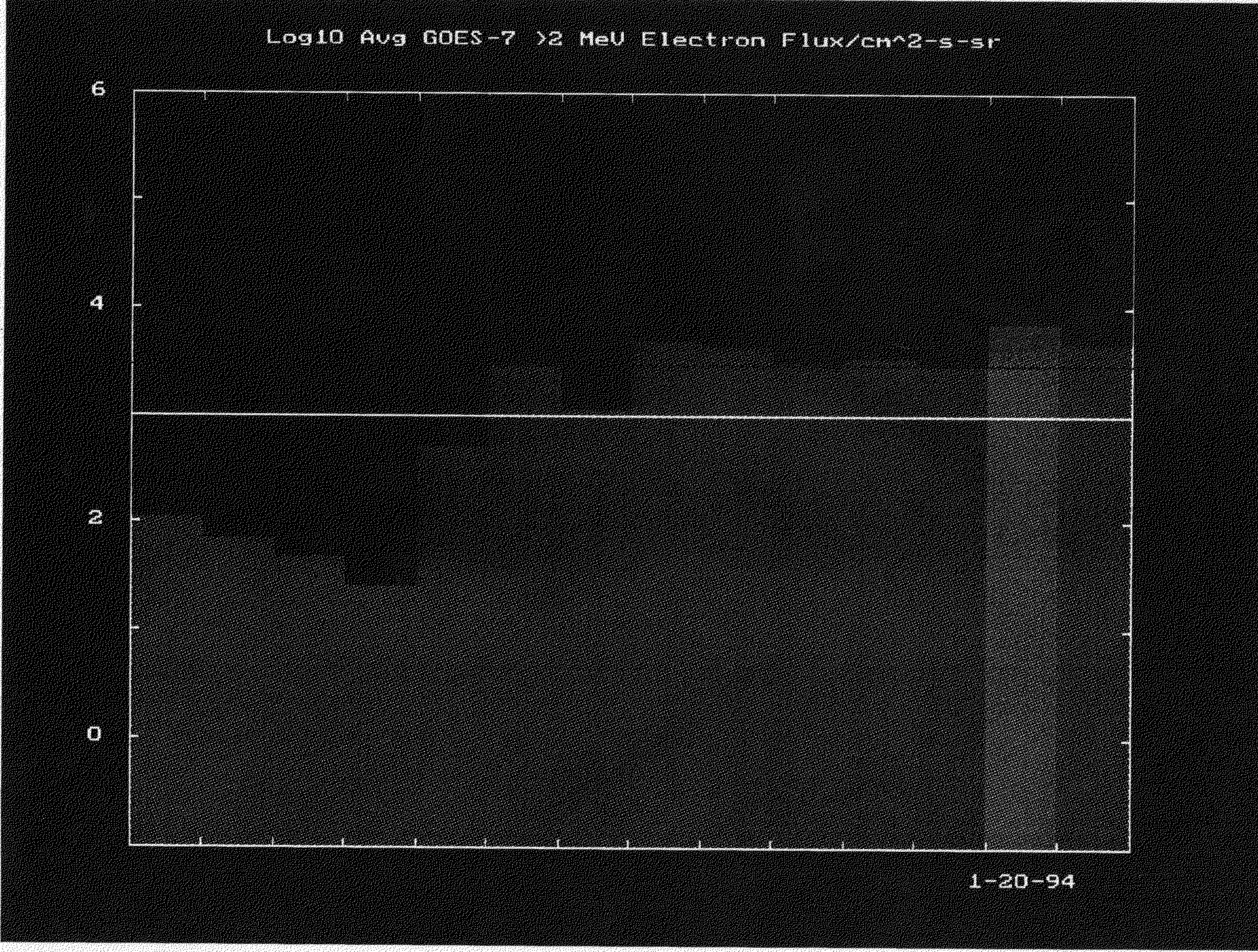
Fraction Transmitted
1
0.8
0.6
0.4
0.2
0
10
15
20
25
30
35
40
45
mils, Al
Electron
Energy, MeV
0.3
0.4
0.5
0.6
0.8
1
1.5
2
2.5
3
4
5

History of Internal Charging

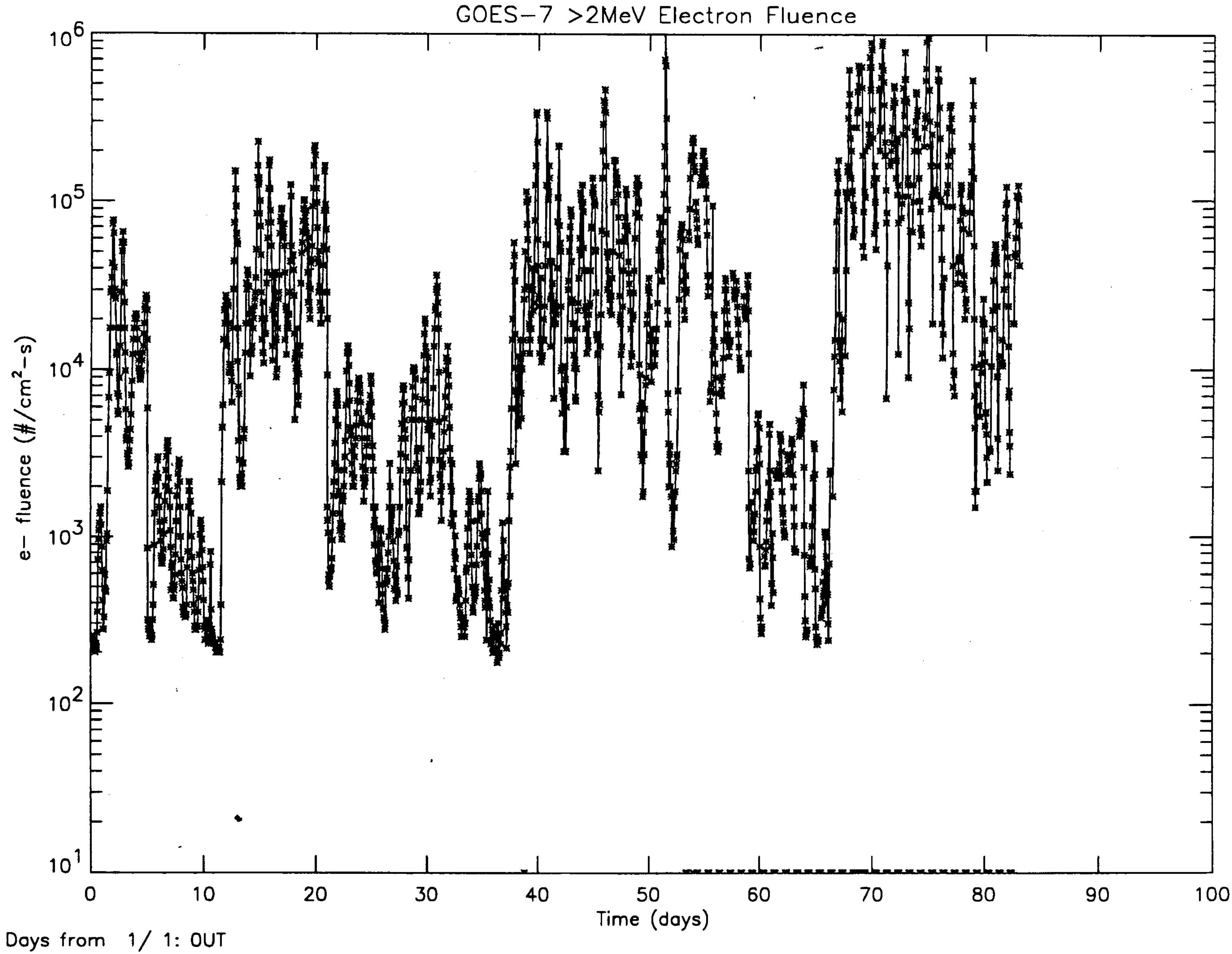
- Spacecraft Anomalies
  - DSP (1980 - 1982)
    - Vampola, J. Electrostatics, 20, 21-30, 1987
  - ANIK (Jan 20-21, 1994)
  - Band B (Classified)
- Spacecraft Measurements
  - SCATHA
    - Pulse Analyzer (Aerospace)
    - Transient Pulse Monitor (SRI)
  - CRRES Internal Discharge Monitor
- Laboratory Measurements
  - Coakley (1986)
  - Mallon (1982)

DSP Star-Sensor Anomalies





Log10 Avg GOES-7 >2 MeV Electron Flux/cm^2-s-sr
6
4
2
0
1-20-94


GOES-7 >2MeV Electron Fluence
e- fluence (#/cm²-s)
10⁶
10⁵
10⁴
10³
10²
10¹
0
10
20
30
40
50
60
70
80
90
100
Time (days)
Days from 1/ 1: 0UT

Band-B Anomaly Characteristics

- At first turnon on orbit the signal from Band B on a classified payload was degraded ~ -32 dB
- Telemetry data indicated anomalous bias current for preamplifier
  - Supply current increased by 2 to 4 mA at the power converter when the first stage was turned off
  - Expected supply current to decrease by ~ 1 mA when first stage is turned off
- SPICE analysis for DC model of "burned out" preamp matched telemetry data
  - Modeled as a gate-to-source short
- Failure occurred in four preamps in two identical fixed feeds

Root-Cause Analysis

- Many potential causes of the failure were investigated by numerous Aerospace and contractor personnel
  - ESD
  - Antenna
  - External RF (e. g. nearby radars)
  - Lightning
  - "Welding" Incident
  - Interconnects
  - Power supply lines
  - Piece part quality
  - Mechanical
  - Many other causes enumerated on large fishbone diagram
- Most likely cause: ESD
  - Internal charging in the feed electronics induced by passage of the spacecraft through the Van Allen radiation belts: two 4-hour charging periods per day

Preamplifier Damage Threshold Measurement

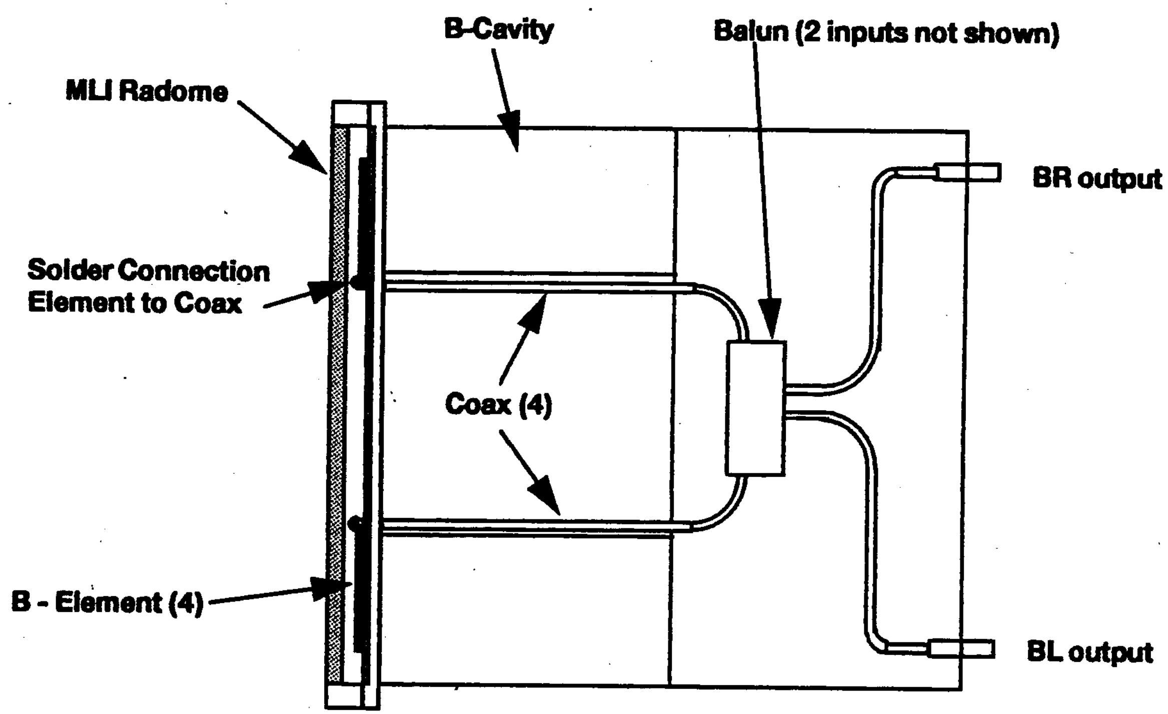
- 2 brassboard preamplifiers were tested to burned-out using pulse-modulated rf to simulate ESD event pulses
  - Pulse widths used were 100 ns and 10 ns to correspond with the measured duration of the ESD events
- Compared damage threshold with energy in discharges from beam tests
- Concluded that burnout from ESD events was probable cause

ESD Opportunities

- Radome over feed is Kapton MLI, very close to top hat
  - Shape dictated by integration needs
  - No ESD bleed coating on radome
  - Deep charging and surface charging methods being analyzed
  - Gathering orbital geomagnetic data
  - Will calculate atmospheric charging during ascent
- Previous radome had large separation to feed
  - No ESD bleed coating was used
  - No history of ESD events or damage

Feed Geometry

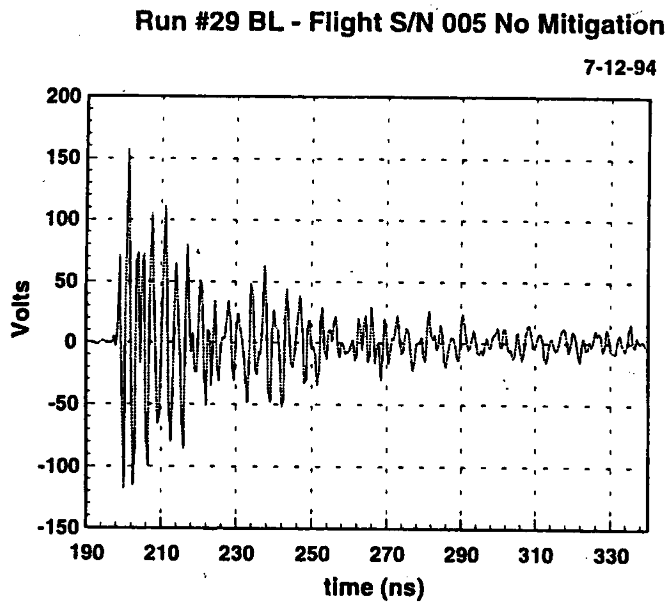
Cross-Sectional View



Charging Experiments

- **The basic idea**
  - Charge the feed with an electron beam having “realistic” energy and flux and capture any discharge event signals at the output of Band B
  - Calculate the power and energy of any observed discharge events
  - Compare the energy in the discharge event with the measured energy damage threshold for the preamplifier
- **Problems**
  - Space charging environment has a continuous energy distribution while Dynamitron electron beam is monoenergetic
  - In space electrons come from all directions
  - Maximum flux obtainable over the energies required limited to 2.5 x 10^8 electrons/cm^2-sec; actual environment may exceed this on rare occasions

Band-B Discharge Event



- Signal measured at the Band-B LH polarization output
- Amplitude 280 V peak-to-peak
- Energy in 100 ns window 2300 nJ
- Burnout threshold for discrete MESFET is between 50 and 500 nJ for 100 ns pulses

Comparison of Laboratory Simulation Environment with Space Environment

- AE8MAX
  - >350 keV average flux for orbit is 2.7×10^6 elec/cm^2-s
- S/N 005
  - Discharged at a fluence ~ 5×10^9 elec/cm^2
  - 1,800 s to discharge at AE8MAX level
- GOES-7 measurements of > 2 MeV electrons at geosynchronus orbit
  - Average flux for several days after launch was > 2×10^4 elec/cm^2-s-sr
  - Extremely high value (98th - 99th percentile)
- Conclude that there was more than adequate time to have damaging internal discharges in flight before turnon

Summary

- Anomalous performance of Band-B preamplifiers was noted at first turn on
- SPICE modeling pointed toward burnout of the first stage MESFETS
- Root cause was determined to be ESD from internal charging by testing conducted at JPL on engineering and spare units
- Mitigation efforts resulted in a timely fix for the next flight with minimal system impact (but a lot of work)

Lessons Learned

- Design changes from previous programs require systems tests and analyses
  - One must be skeptical of "Qual by Similarity" without adequate analysis
  - Baseline requirements must be verified for new design
  - Design changes should be tested if the environmental effects cannot be clearly understood by analysis
- Survival requires proper materials selection and robust circuit design and components
- "Off the shelf" hardware must be carefully analyzed to assure that it is suitable for the intended application and environment
- New requirements, materials and processes require a new systems analysis
  - e.g. Radome vs. Raflat

Anomaly Study for the DoD Space Architect

Overview of Results

- 326 data forms are contained in the data collection
  - Range from one occurrence to 617 occurrences per form
- 299 have cause diagnosed as the space environment
- 155 have impacts obtained from the referenced documents
  - Virtually none of the impacts are quantified in terms of the cost of the impact
  - It is possible to estimate the duration of the impact on a user from 173 of the forms
  - 137 have permanent degradation that may have impacted users
    - Loss of a subsystem
    - Random part failure
    - Mission or sensor degradation
    - Solar array degradation
    - Mission loss

Distribution of Forms by Anomaly Diagnosis

Diagnosis		Number
ESD & Charging:		
ESD - Internal Charging		74
ESD - Surface Charging		59
ESD - Uncategorized		28
Surface Charging		1
	Total:	162
SEUs:		
SEU - Cosmic Ray		15
SEU - Solar Proton Event		9
SEU - South Atlantic Anomaly		20
SEU - Uncategorized		41
	Total:	85

SCATHA Satellite

Spacecraft Charging at High Altitude
1979–1991

- Air Force/Space Test Program research satellite
- Measured the plasma environment
- Monitored the electrostatic potential of representative satellite surface materials
- Measured the characteristics of the rf from electrostatic discharges

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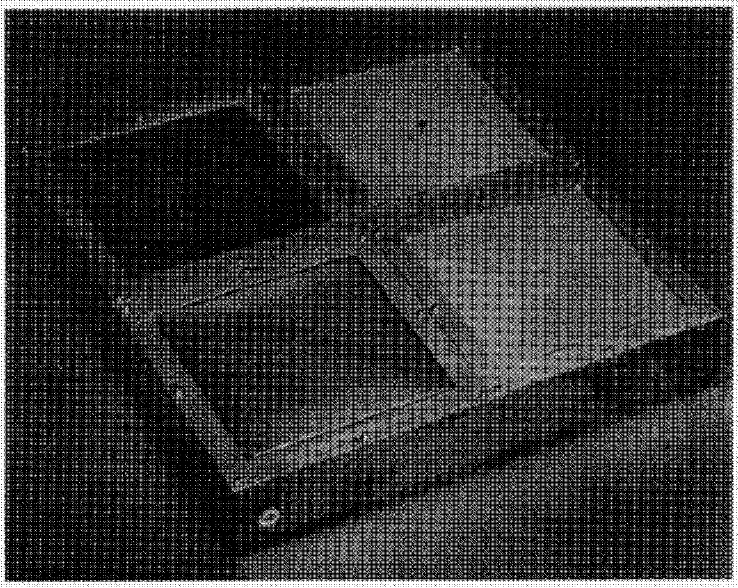
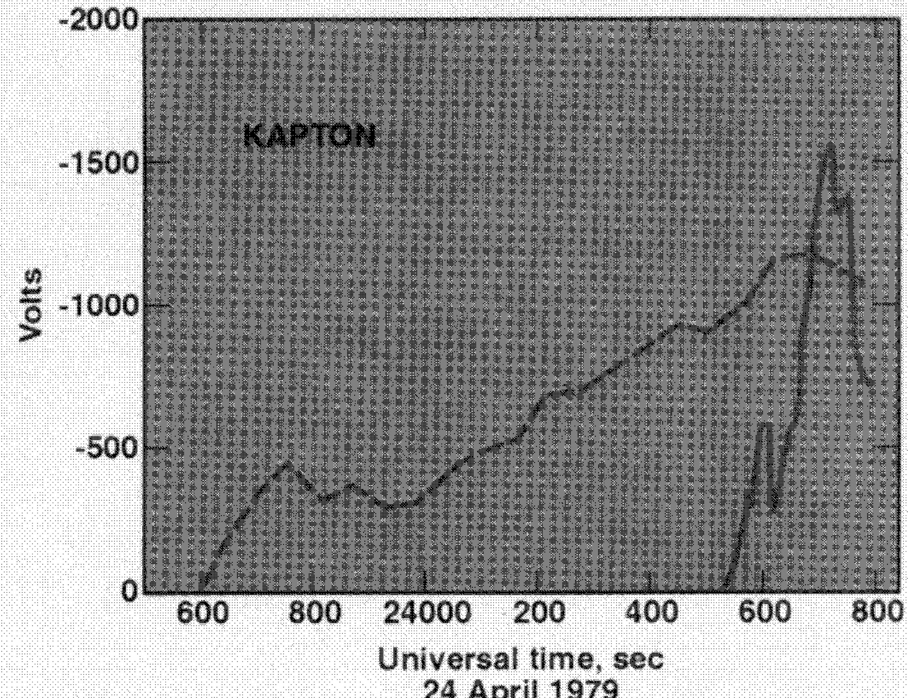
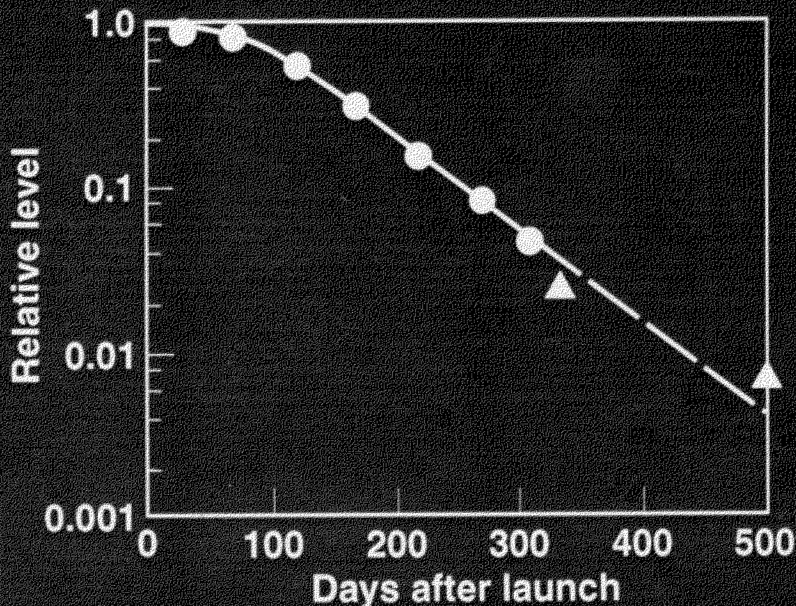
SCATHA Spacecraft Surface Potential Monitor

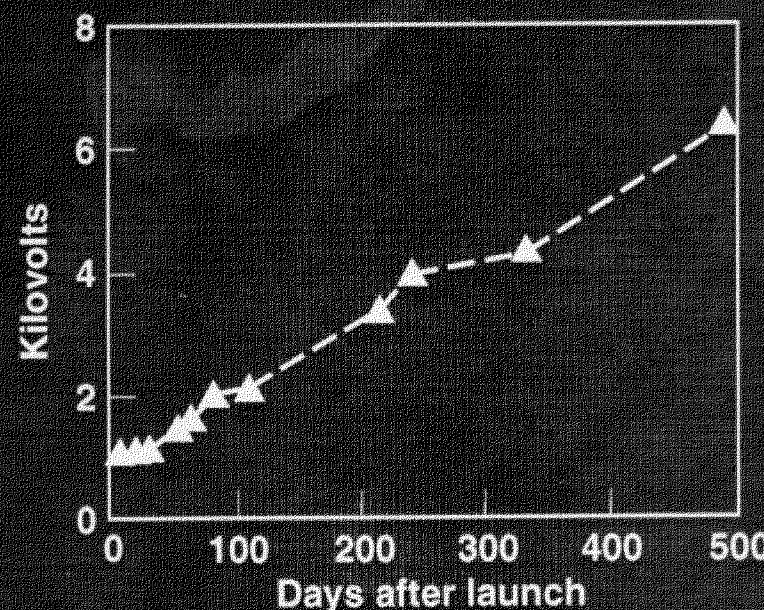




Charging Level of Kapton Sample Relative to Its Level, Right After Launch



Maximum Bulk Charging Between the Teflon Sample and Space-Vehicle Ground



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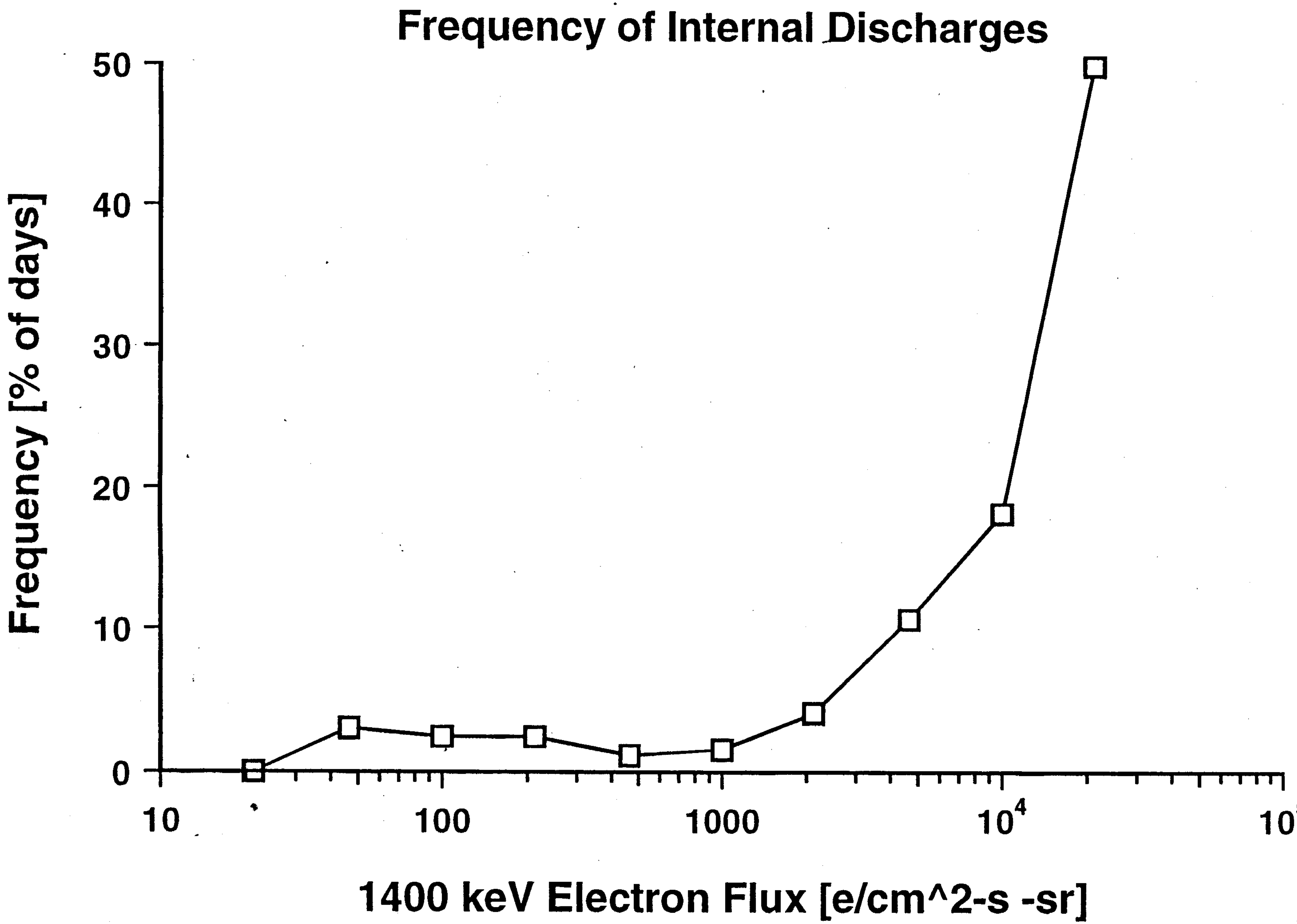
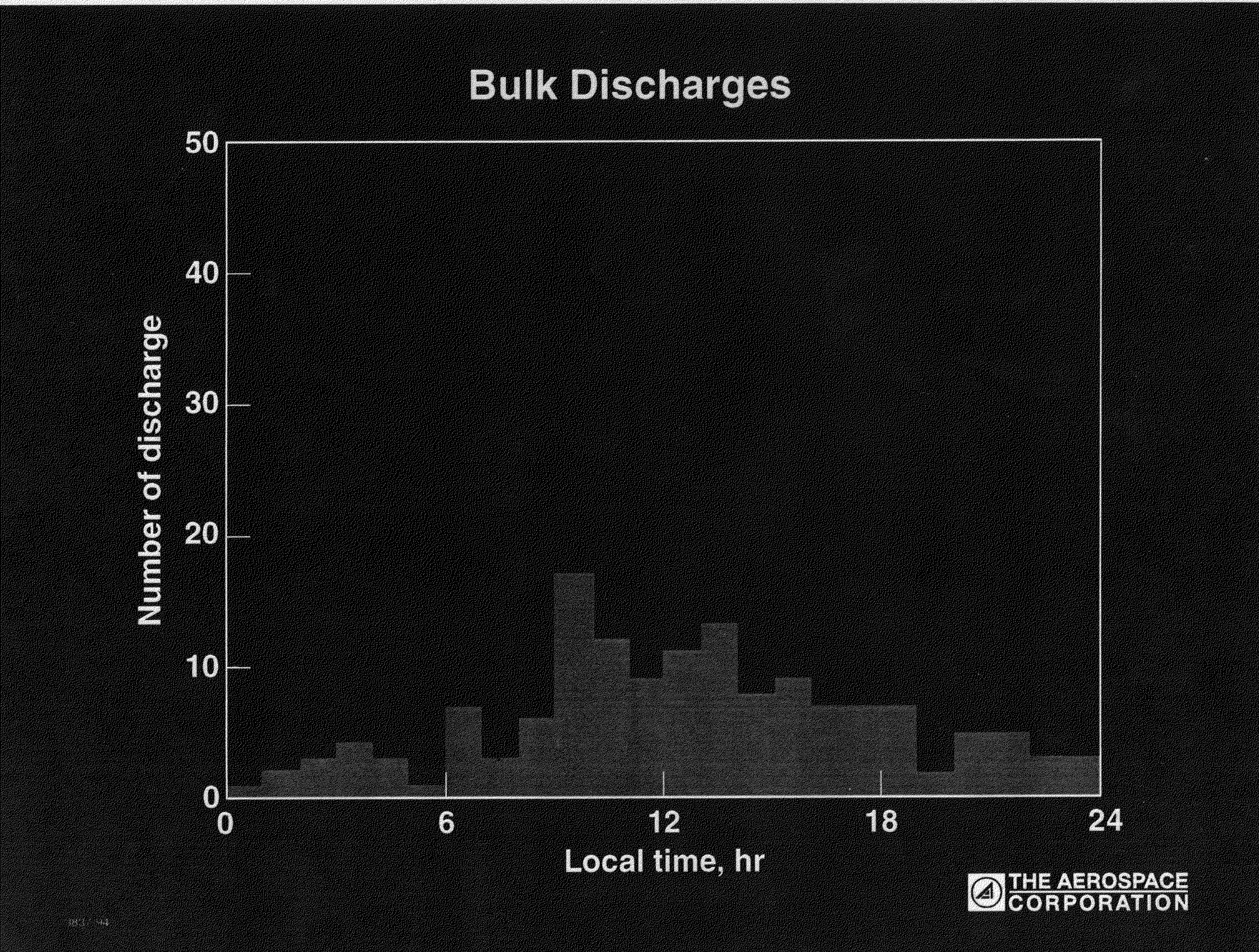
3814-94


Frequency of Internal Discharges
Frequency [% of days]
50
40
30
20
10
0
10
100
1000
10^4
10^5
1400 keV Electron Flux [e/cm^2-s -sr]



Bulk Discharges
50
40
30
20
10
0
Number of discharge
0
6
12
18
24
Local time, hr
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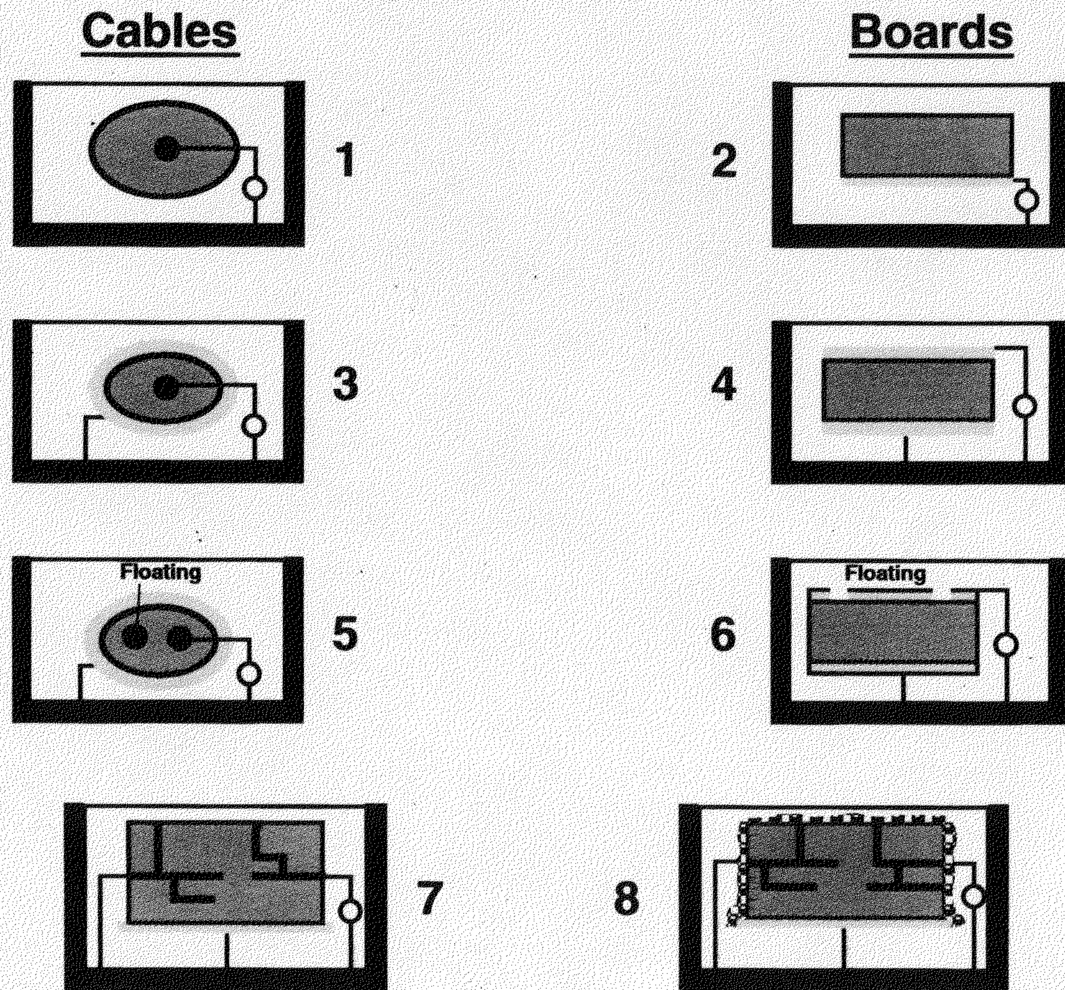
CRRES, Internal Discharge Monitor Electrode Geometries



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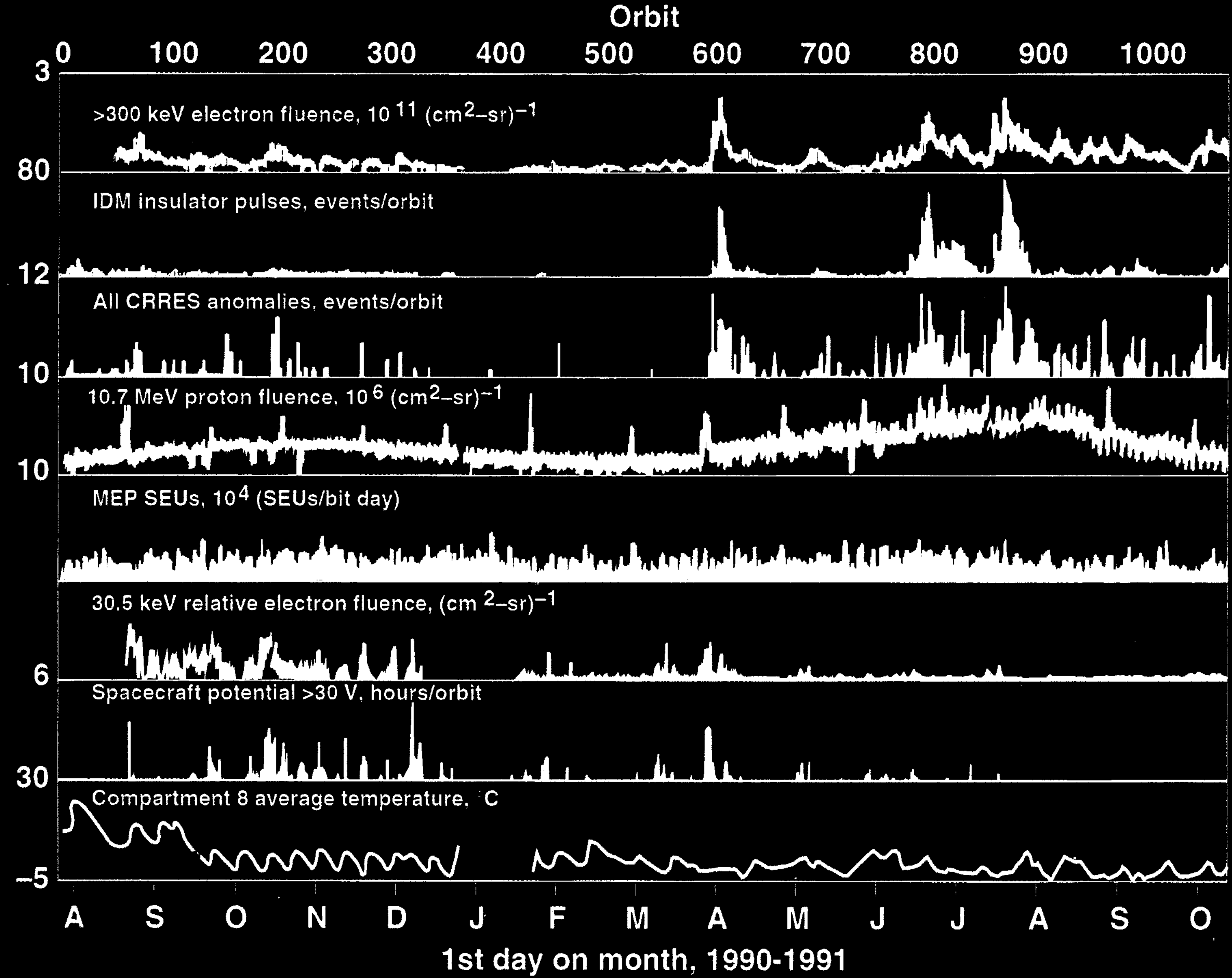
2830-95

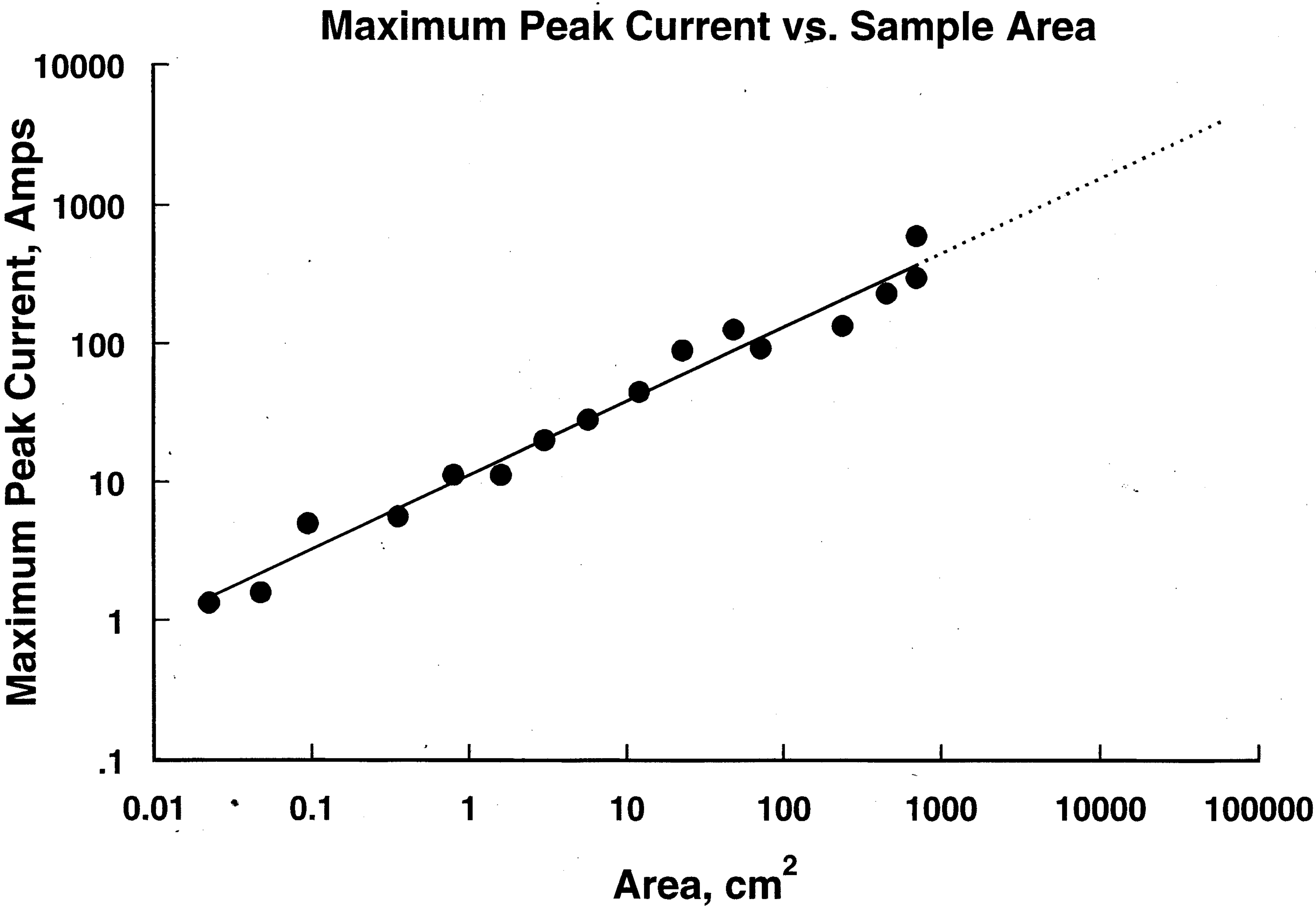
CRRES Anomalies Compared with the Environment



CRRES Internal Discharge Monitor

Cha	Sample Description	VM	Geom	Pulses
1	SC18 wire type EY, 7 mil PTFE	1	1	9, V < 16
2	TS triax cable, Raychem 44/2421	5	5	0
3	MEP G10 solithane coated only	50	7	2, V < 70
4	FR4 epoxy fiberglass, 0.317 cm	5	2	1433, V < 25 16, 25 < V < 60 252, V > 60
5	RG: 316 cable, Belden 83284	0.5	3	0
6	Solid Al jacket RG402 cable	1	3	1, V < 30
7	Alumina, 0.102 cm, Cu electrodes	40	6	0
8	FR4 epoxy fiberglass, 0.317 cm	1	4	516, V < 45 1, V > 60
9	FEP Teflon, 0.229 cm, Al electr	100	6	23, V < 70 1, V > 70
10	FEP Teflon, 0.229 cm, Al electr	0.2	4	0
11	PTFE fiberglass, 0.229 cm, 3M "250"	1	4	0
12	FR4 epoxy fiberglass, 0.317 cm	5	2	903, V < 40 2, 40 < V < 60 4, V > 60
13	FR4 epoxy fiberglass, 0.317 cm	100	6	101, V < 60 8, V > 60
14	MEP G10 solithane, leaky paint	<1	8	0
15	FR4 epoxy fiberglass, 0.119 cm	0.25	2	24, V < 40 19, V > 60
16	PTFE fiberglass, 0.229 cm, 3M "250"	0.2	2	280, V < 30 2, 30 < V < 60 19, V > 60

Area Scaling for Surface Discharge on a Dielectric


Maximum Peak Current vs. Sample Area
Maximum Peak Current, Amps
10000
1000
100
10
1
.1
0.01
0.1
1
10
100
1000
10000
100000
Area, cm2

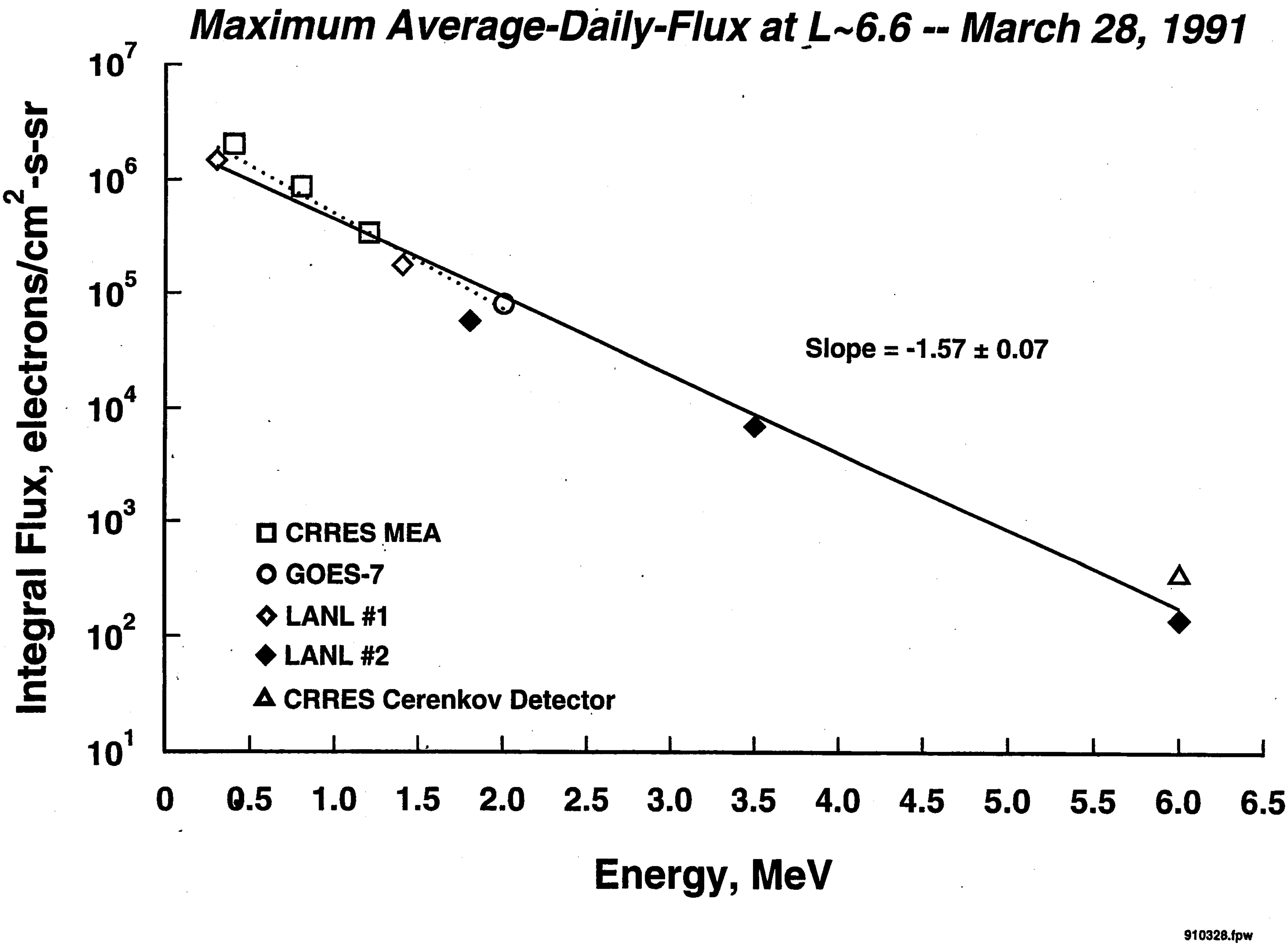
Area Scaling

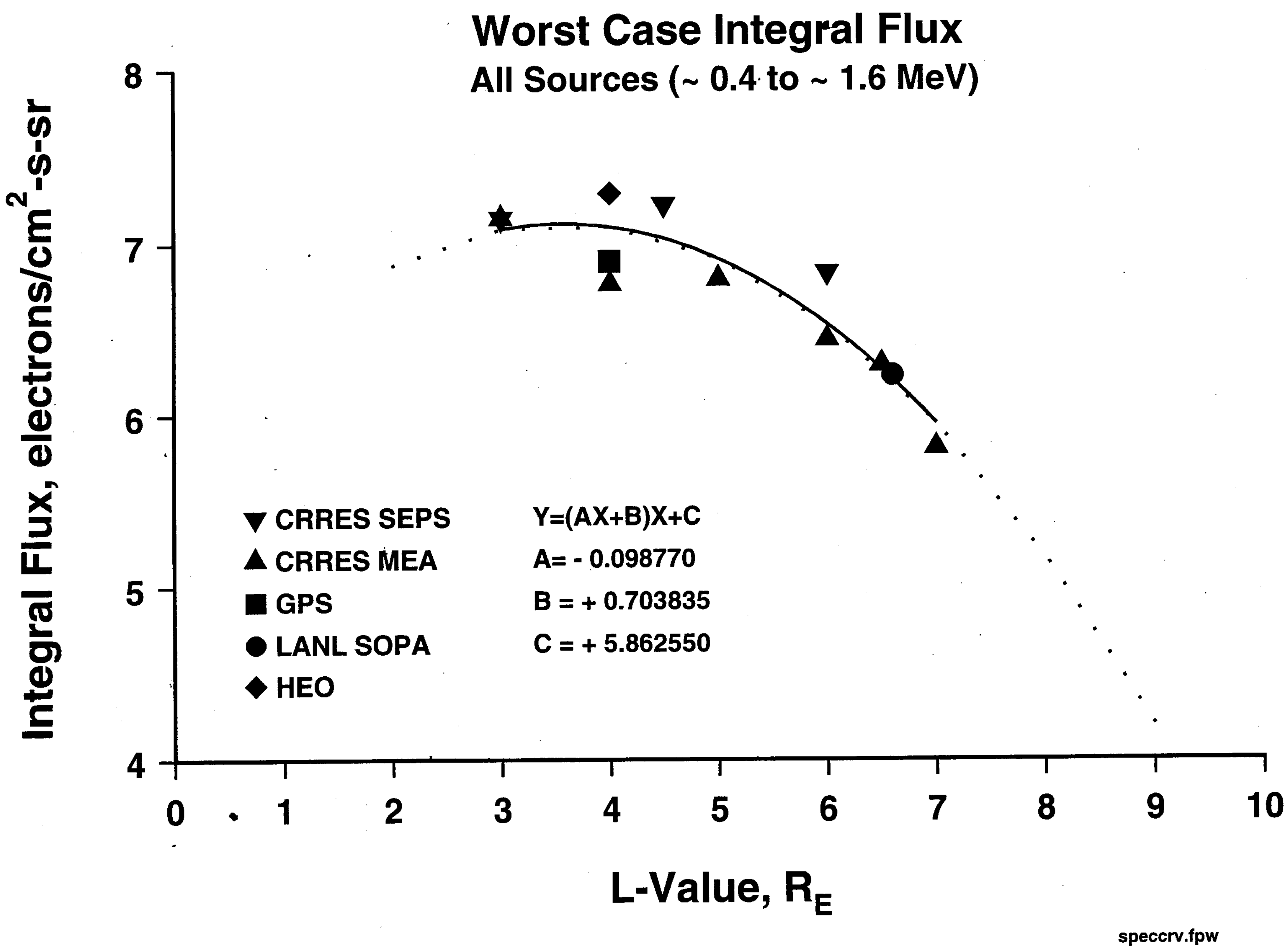
- I_{max} is the maximum peak current
- Koons
  - $\ln(I_{\max}) = 0.537\ln(Area) + 2.415981$
  - Area in cm^2
- Elkman
  - $\ln(I_{\max}) = 0.575\ln(Area) + 2.29253$
  - Area in cm^2

Internal Charging Environment for MAP

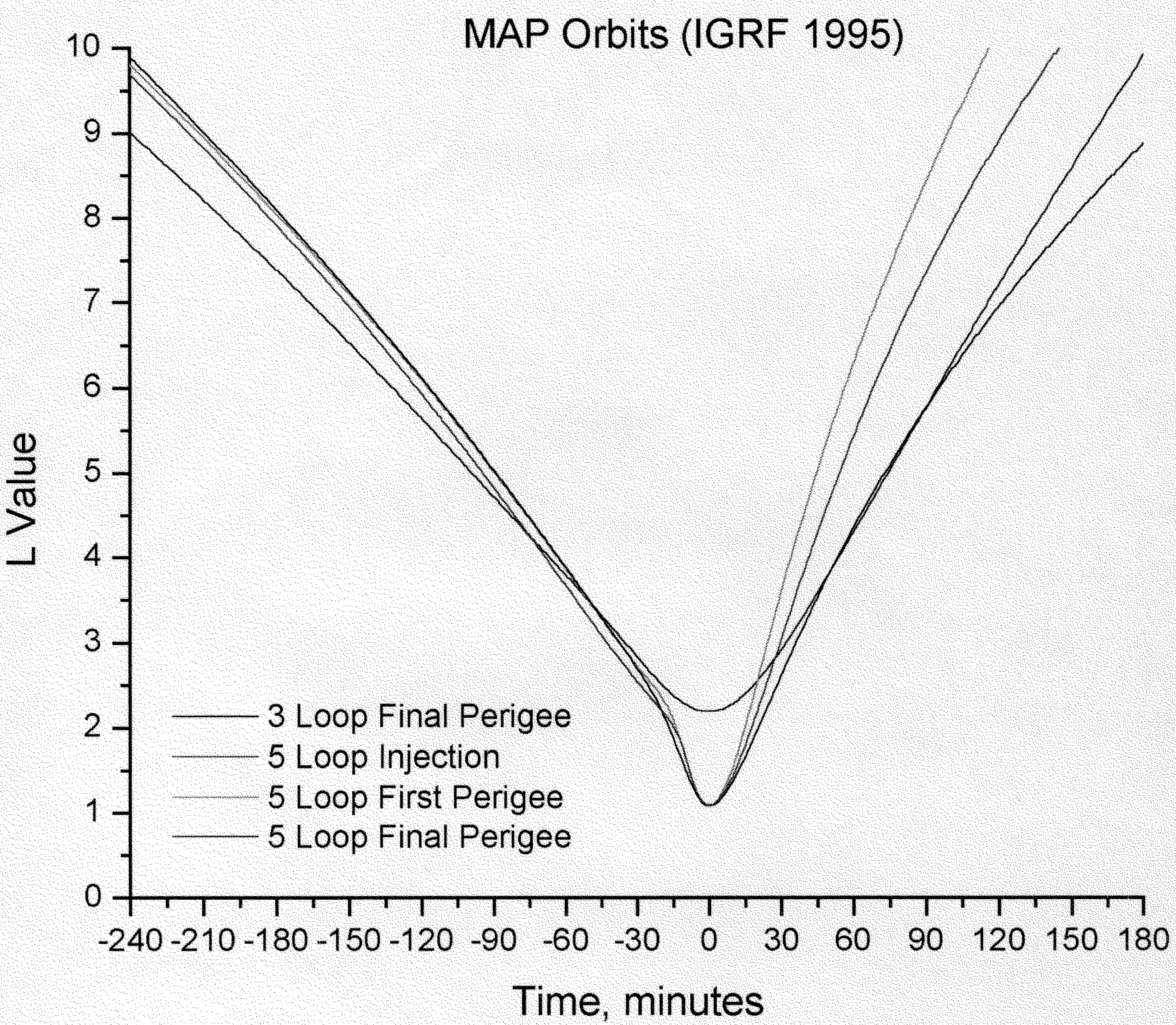
by

Joe Fennell
Harry Koons
and
Mike McNab

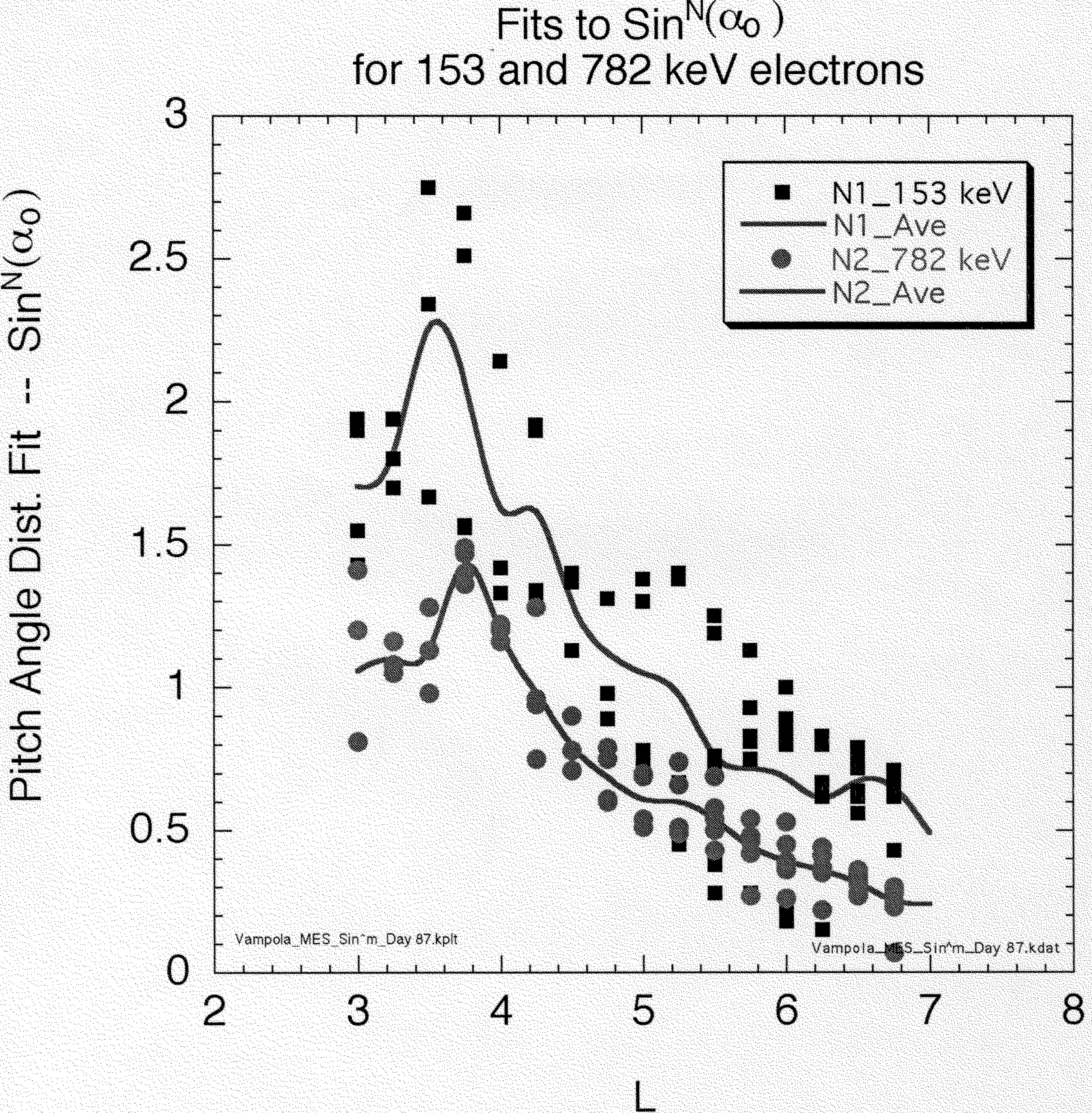

Maximum Average-Daily-Flux at L~6.6 -- March 28, 1991
Integral Flux, electrons/cm^2-s-sr
10^7
10^6
10^5
10^4
10^3
10^2
10^1
Slope = -1.57 ± 0.07
CRRES MEA
GOES-7
LANL #1
LANL #2
CRRES Cerenkov Detector
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
Energy, MeV
910328.fpw

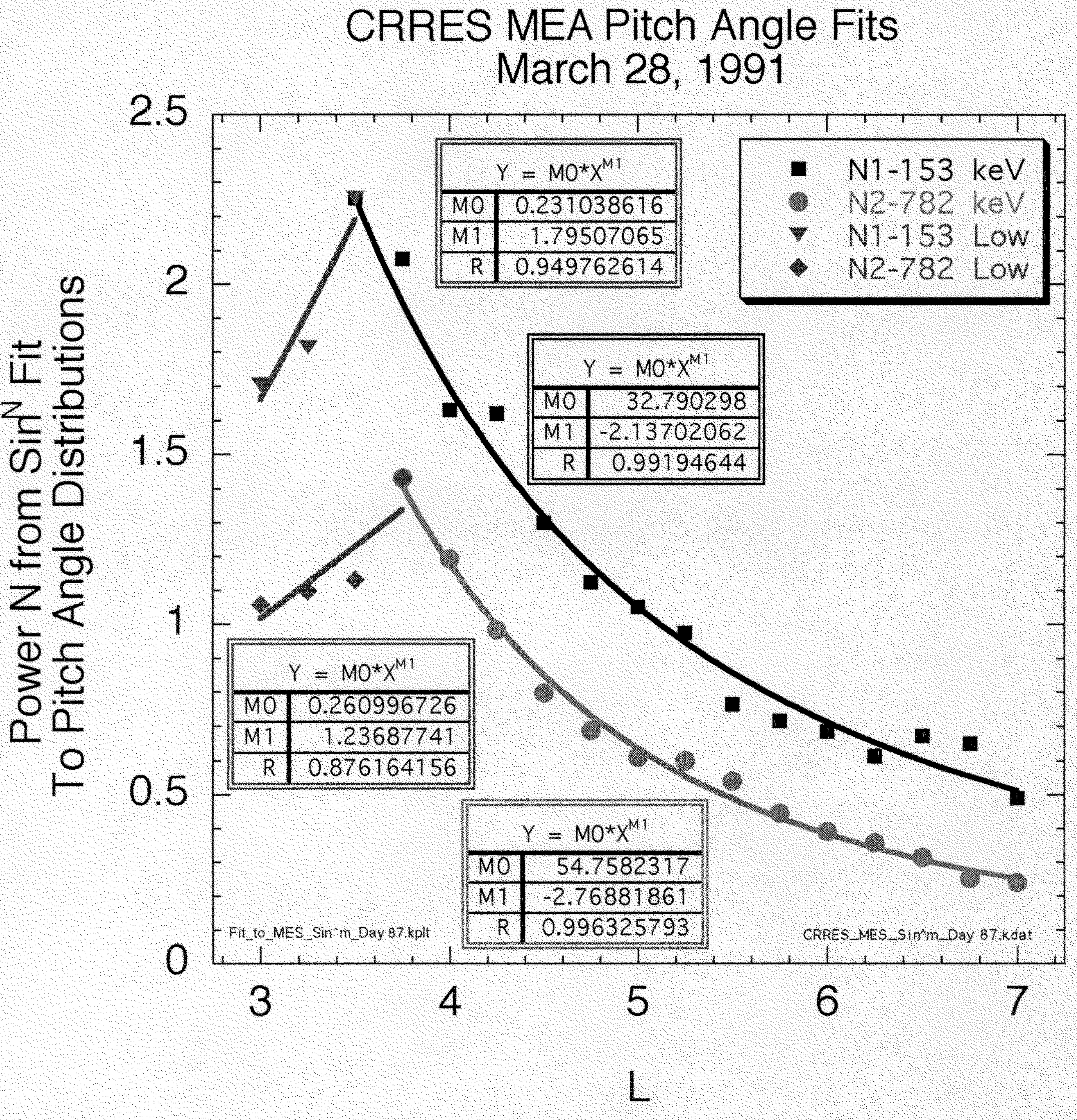


Worst Case Integral Flux
All Sources (~ 0.4 to ~ 1.6 MeV)
Integral Flux, electrons/cm^2-s-sr
L-Value, R_E
4
5
6
7
8
0
1
2
3
4
5
6
7
8
9
10
CRRES SEPS
CRRES MEA
GPS
LANL SOPA
HEO
Y=(AX+B)X+C
A= - 0.098770
B = + 0.703835
C = + 5.862550
speccrv.fpw

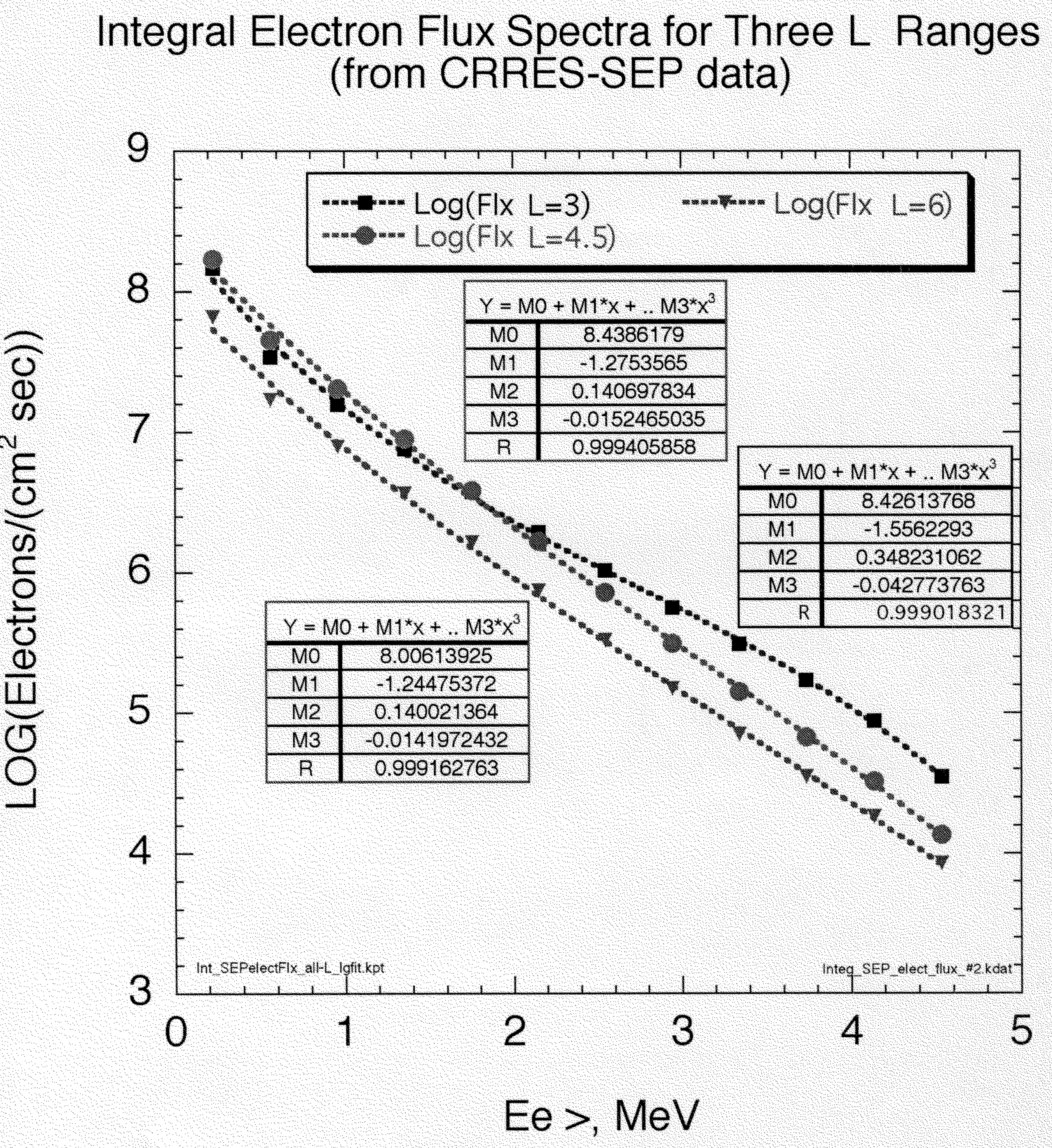


MAP Orbits (IGRF 1995)
L Value
Time, minutes
3 Loop Final Perigee
5 Loop Injection
5 Loop First Perigee
5 Loop Final Perigee

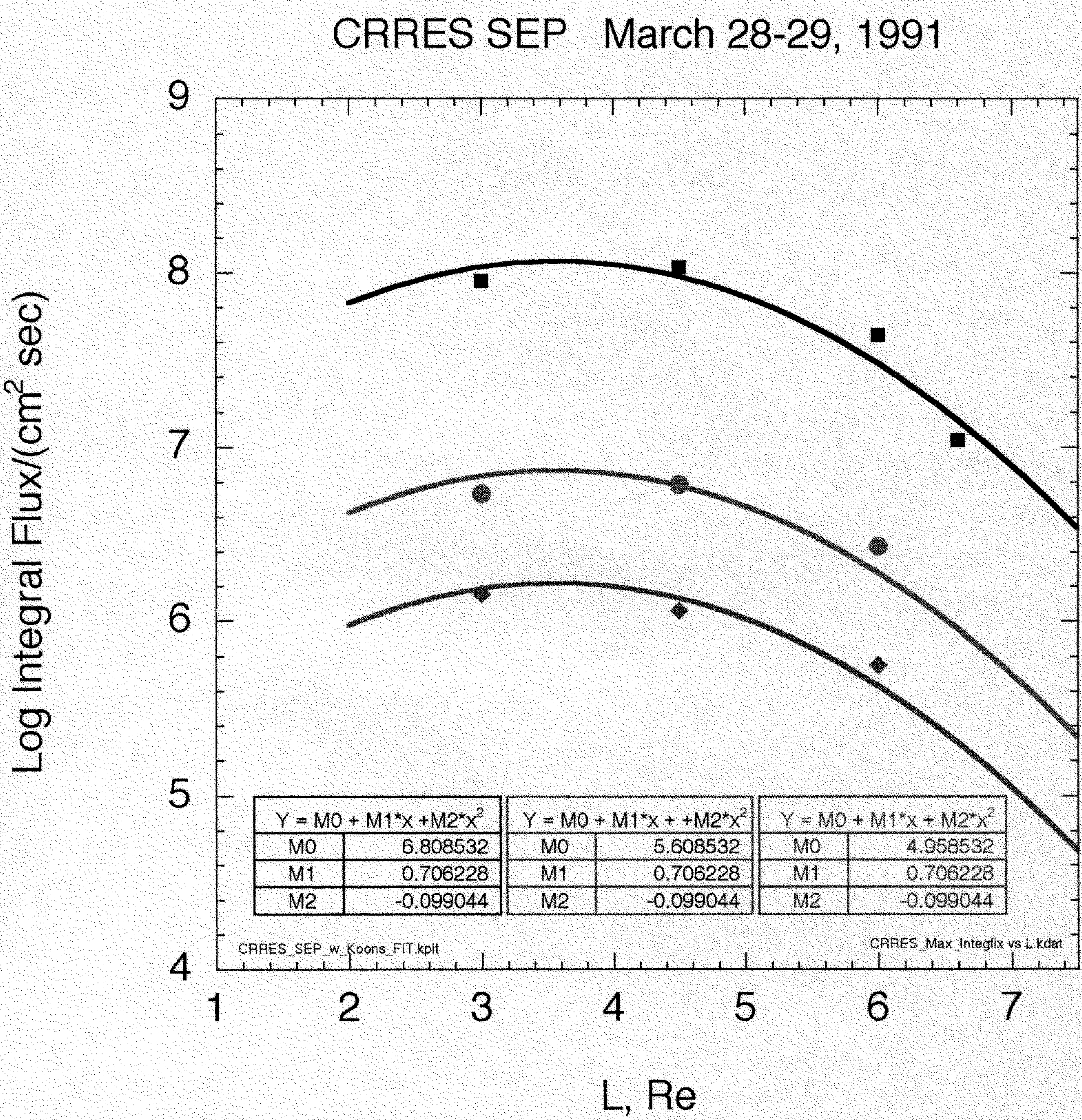

Fits to $\mathrm{Sin}^N(\alpha_o)$
for 153 and 782 keV electrons
Pitch Angle Dist. Fit -- $\mathrm{Sin}^N(\alpha_o)$
L
N1_153 keV
N1_Ave
N2_782 keV
N2_Ave
Vampola_MES_Sin^m_Day 87.kplt
Vampola_MES_Sin^m_Day 87.kdat
0
0.5
1
1.5
2
2.5
3
2
3
4
5
6
7
8



CRRES MEA Pitch Angle Fits
March 28, 1991
Power N from Sin^N Fit
To Pitch Angle Distributions
L
N1-153 keV
N2-782 keV
N1-153 Low
N2-782 Low
Y = M0*X^M1
M0 0.231038616
M1 1.79507065
R 0.949762614
Y = M0*X^M1
M0 32.790298
M1 -2.13702062
R 0.99194644
Y = M0*X^M1
M0 0.260996726
M1 1.23687741
R 0.876164156
Y = M0*X^M1
M0 54.7582317
M1 -2.76881861
R 0.996325793
Fit_to_MES_Sin^m_Day 87.kplt
CRRES_MES_Sin^m_Day 87.kdat
2.5
2
1.5
1
0.5
0
3
4
5
6
7

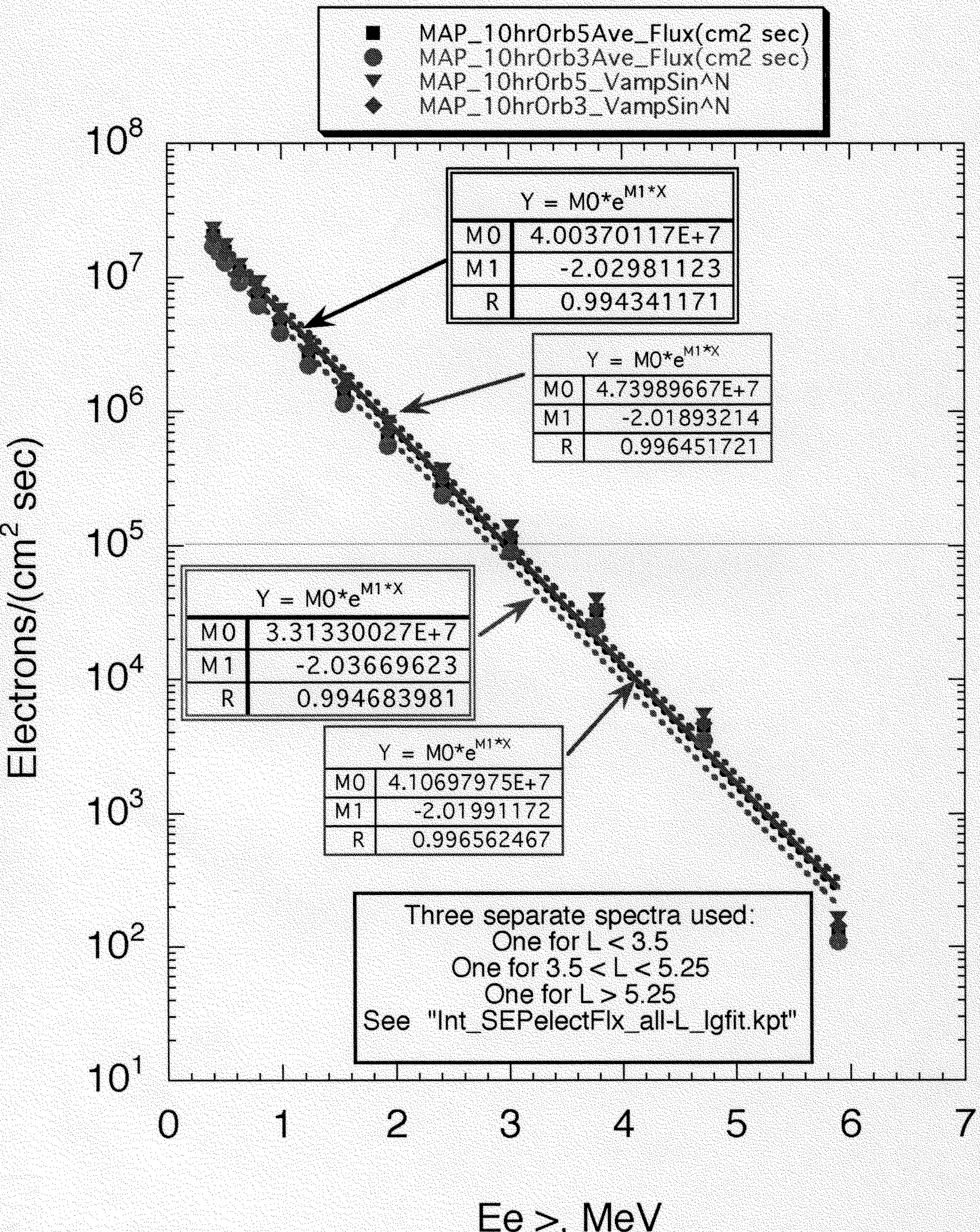


Integral Electron Flux Spectra for Three L Ranges
(from CRRES-SEP data)
Log(Flx L=3)
Log(Flx L=4.5)
Log(Flx L=6)
Y = M0 + M1*x + .. M3*x^3
M0 8.4386179
M1 -1.2753565
M2 0.140697834
M3 -0.0152465035
R 0.999405858
Y = M0 + M1*x + .. M3*x^3
M0 8.42613768
M1 -1.5562293
M2 0.348231062
M3 -0.042773763
R 0.999018321
Y = M0 + M1*x + .. M3*x^3
M0 8.00613925
M1 -1.24475372
M2 0.140021364
M3 -0.0141972432
R 0.999162763
LOG(Electrons/(cm^2 sec))
Ee >, MeV
Int_SEPelectFlx_all-L_lgfit.kpt
Integ_SEP_elect_flux_#2.kdat



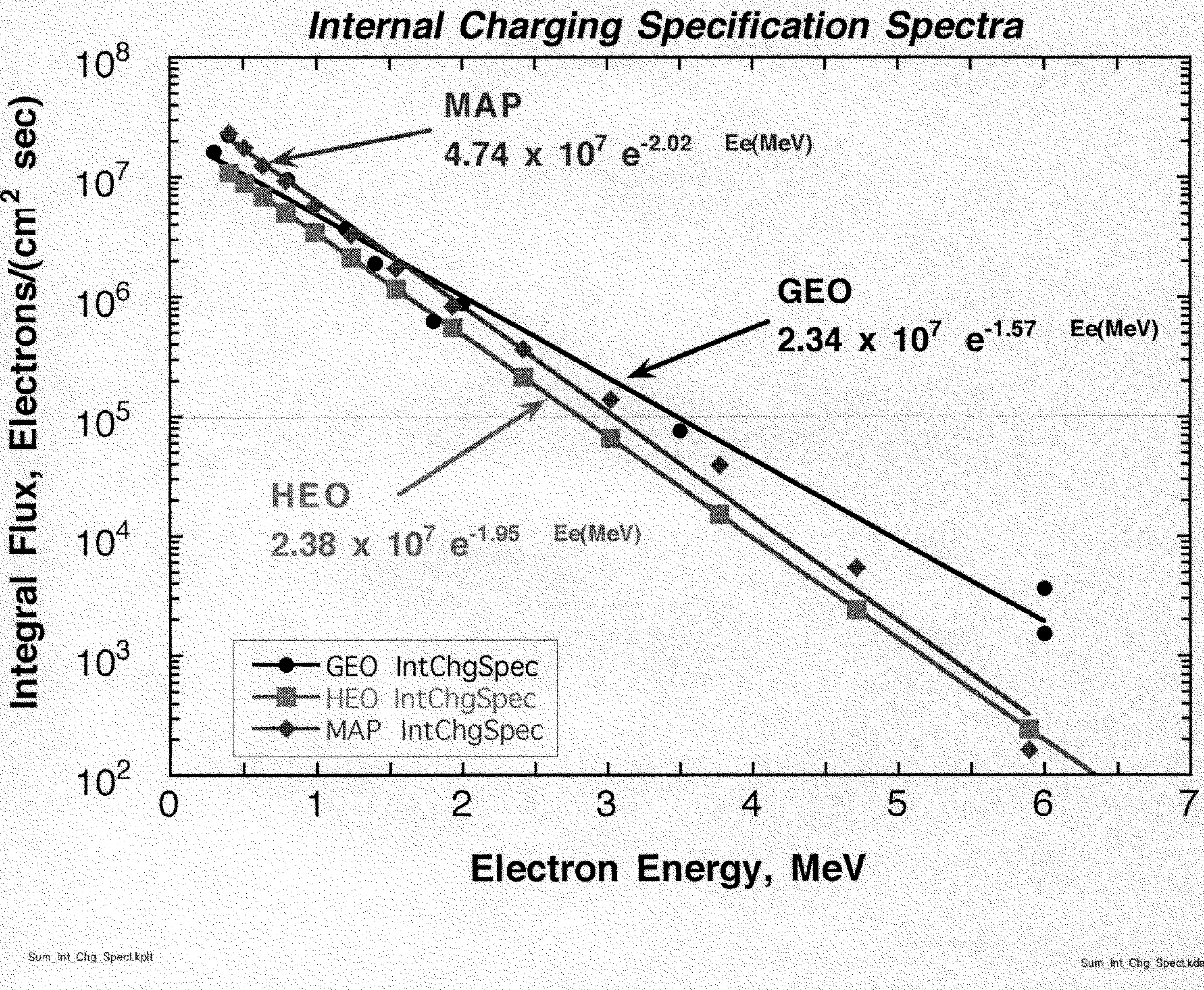
CRRES SEP March 28-29, 1991
Log Integral Flux/(cm^2 sec)
L, Re
9
8
7
6
5
4
1
2
3
4
5
6
7
Y = M0 + M1*x +M2*x^2
M0 6.808532
M1 0.706228
M2 -0.099044
Y = M0 + M1*x + +M2*x^2
M0 5.608532
M1 0.706228
M2 -0.099044
Y = M0 + M1*x + M2*x^2
M0 4.958532
M1 0.706228
M2 -0.099044
CRRES_SEP_w_Koons_FIT.kplt
CRRES_Max_Integflx vs L.kdat

10 Hour Average Integral Electron Flux Spectra for two different MAP orbits.



MAP_10HrAve_Orb5&3_IvsEe.kplt

Integ_SEP_elect_flux_#2.kdat



Internal Charging Specification Spectra
Integral Flux, Electrons/(cm^2 sec)
Electron Energy, MeV
MAP
4.74 x 10^7 e$^{-2.02}$ Ee(MeV)
GEO
2.34 x 10^7 e$^{-1.57}$ Ee(MeV)
HEO
2.38 x 10^7 e$^{-1.95}$ Ee(MeV)
GEO IntChgSpec
HEO IntChgSpec
MAP IntChgSpec
Sum_Int_Chg_Spect.kplt
Sum_Int_Chg_Spect.kdat

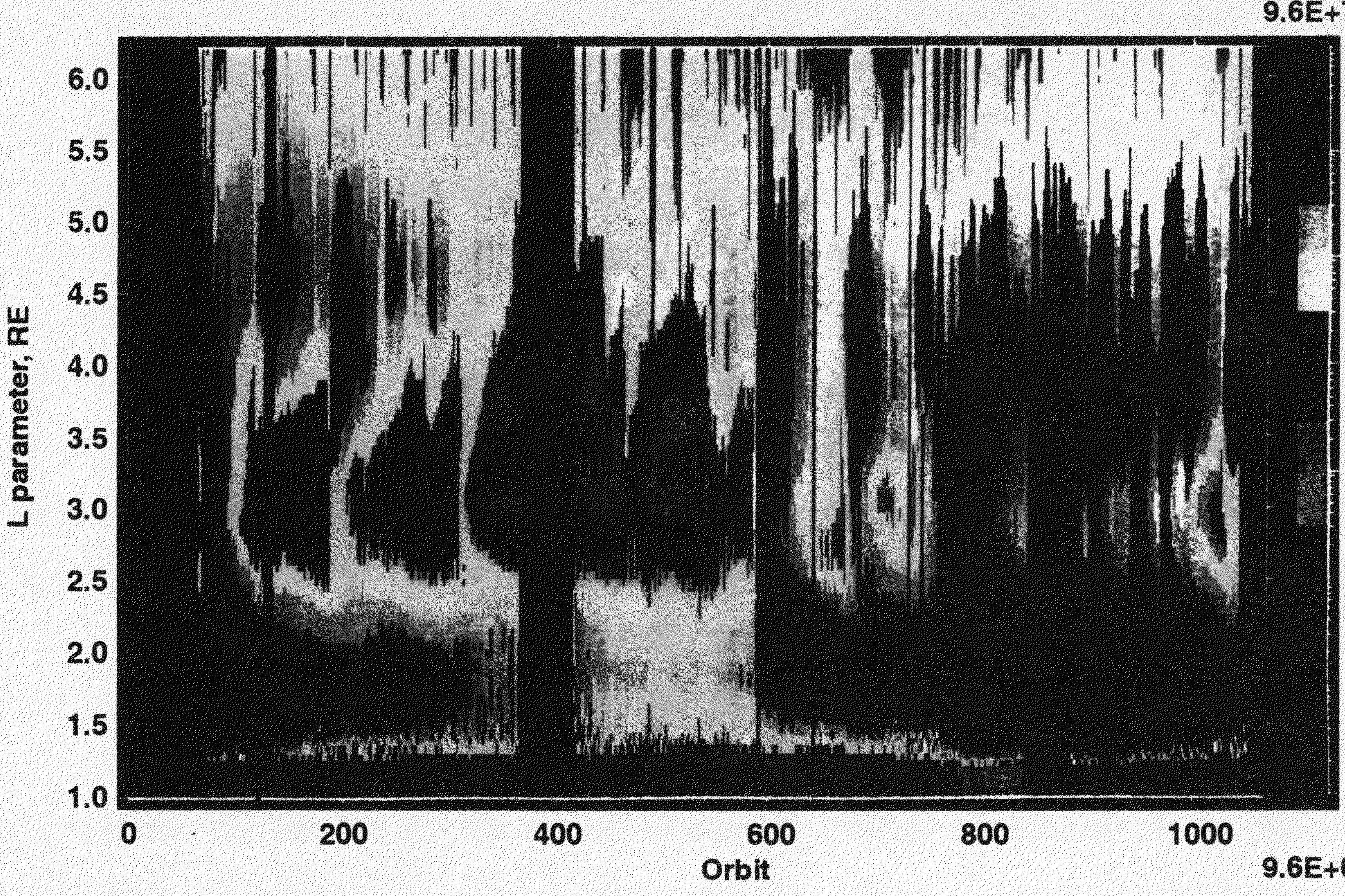
Concept of a “Zero Discharge Limit” and a “Safe Flux Limit”

- Maximum fluence per orbit that did not produce a pulse from the IDM samples on CRRES
  - Orbital period was 10 hours
  - Energies > 150 keV required to penetrate 0.02 cm (7.8 mils) of shielding
  - “In this paper, the reported electron fluxes and fluences have been summed over all energies and are those that are semi-isotropically incident on the samples having been transmitted through the cover plate.”
- Zero Discharge Limit
  - 2×10^{10} electrons / (cm^2 - orbit)
  - Corresponds to an average electron flux of 5×10^5 electrons / (cm^2 - sec)
- Safe Flux Limit
  - “One might wish to add a safety factor and assume that only fluxes below 1×10^5 electrons / (cm^2 - sec) are safe.”
- Applied to ***all*** IDM samples not just cables.

Statistical Properties of CRRES MEA Measurements

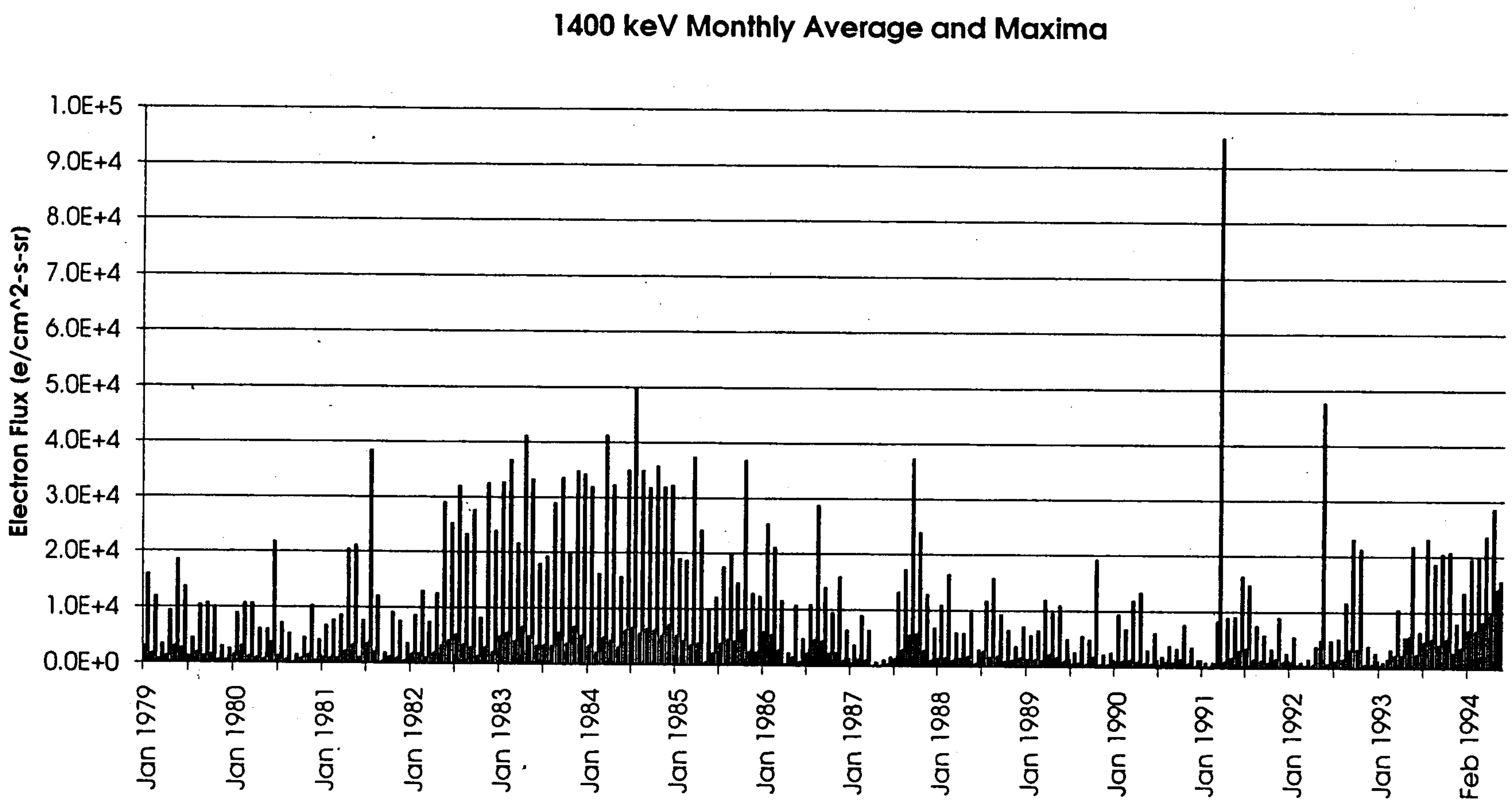
Electron Scatter Detector

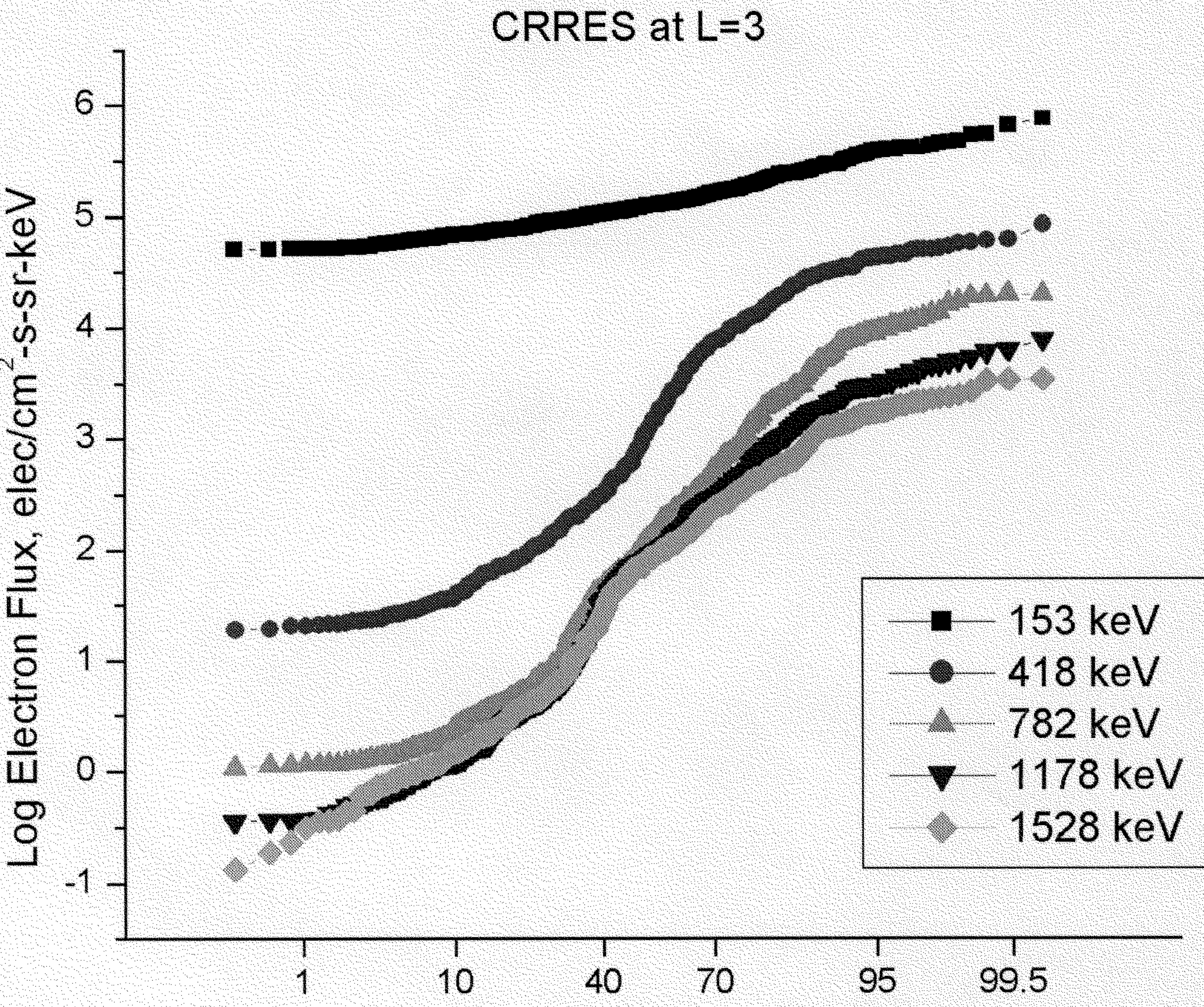
e > 255 keV

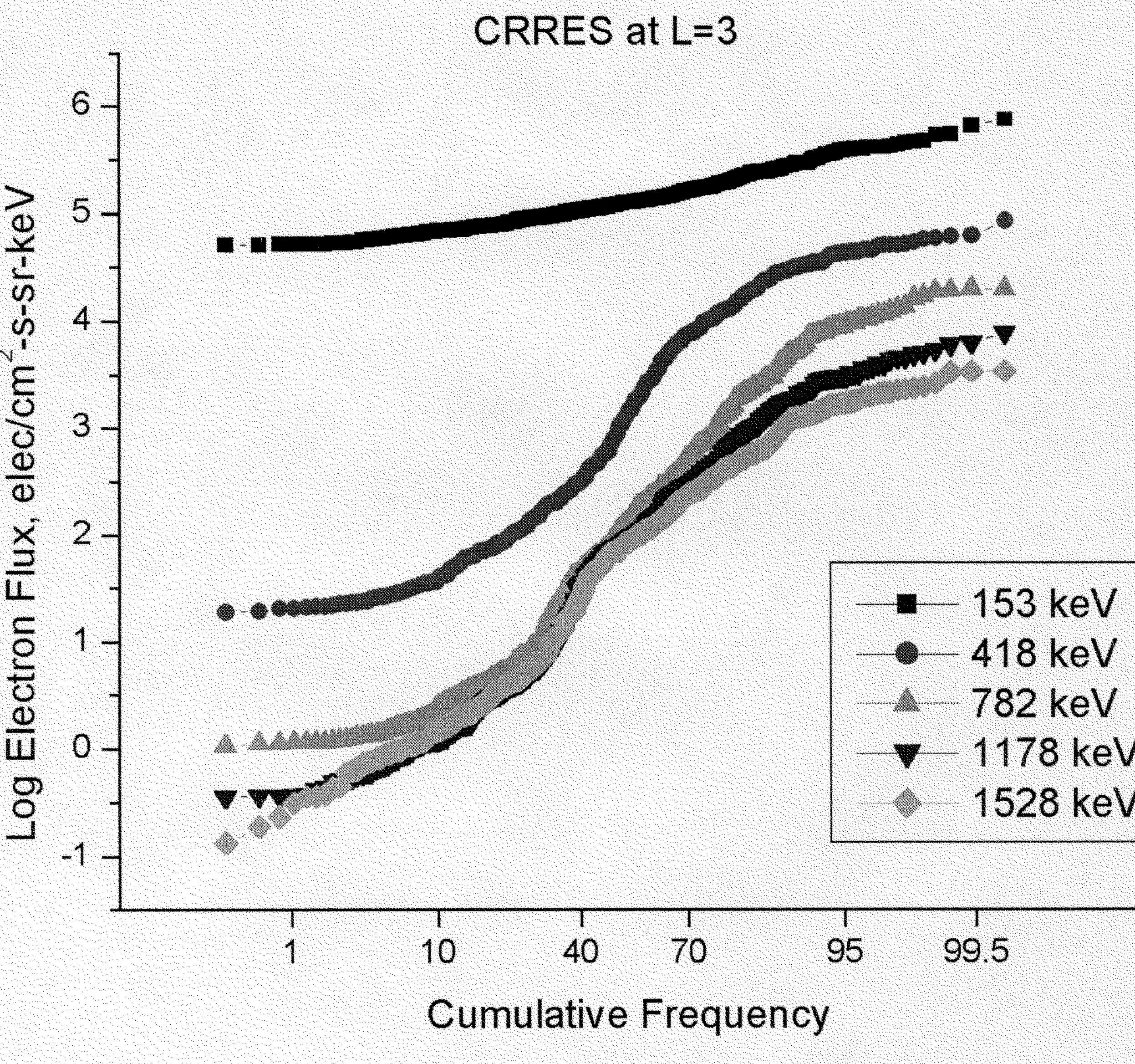


THE AEROSPACE CORPORATION

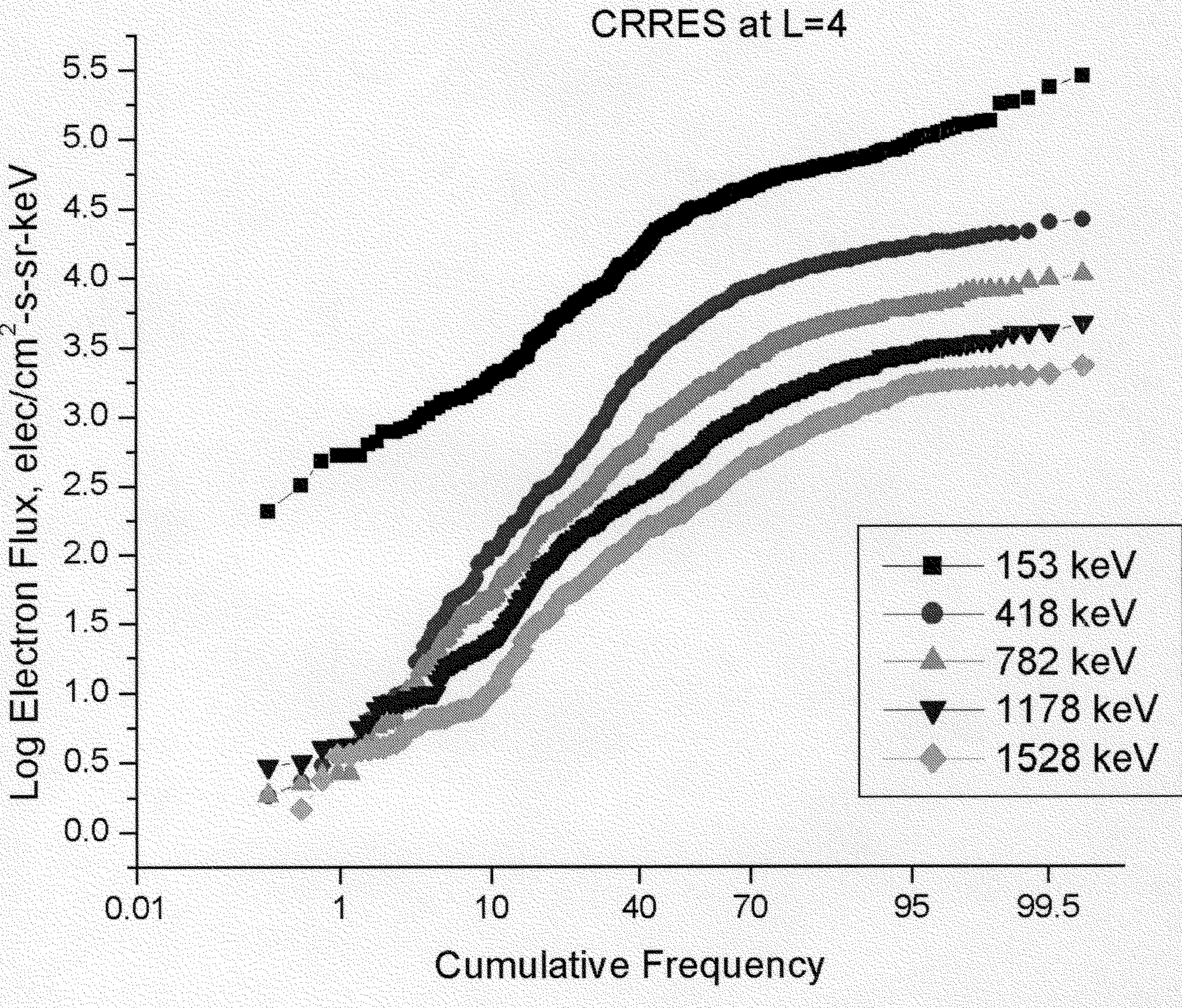
2818-95 B13


1400 keV Monthly Average and Maxima
Electron Flux (e/cm^2-s-sr)
1.0E+5
9.0E+4
8.0E+4
7.0E+4
6.0E+4
5.0E+4
4.0E+4
3.0E+4
2.0E+4
1.0E+4
0.0E+0
Jan 1979
Jan 1980
Jan 1981
Jan 1982
Jan 1983
Jan 1984
Jan 1985
Jan 1986
Jan 1987
Jan 1988
Jan 1989
Jan 1990
Jan 1991
Jan 1992
Jan 1993
Feb 1994

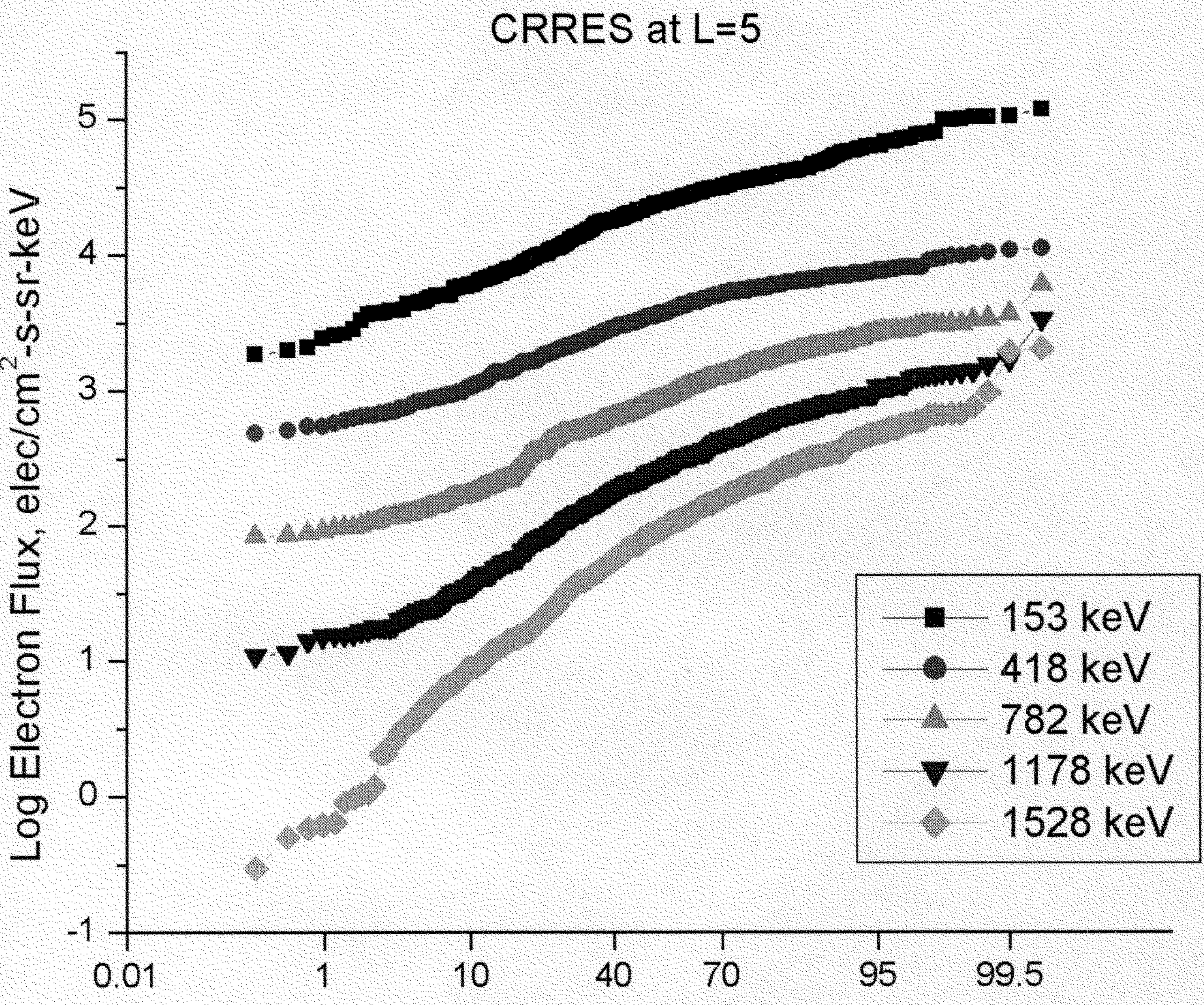

CRRES at L=3
Log Electron Flux, elec/cm2-s-sr-keV
6
5
4
3
2
1
0
-1
1
10
40
70
95
99.5
Cumulative Frequency
153 keV
418 keV
782 keV
1178 keV
1528 keV



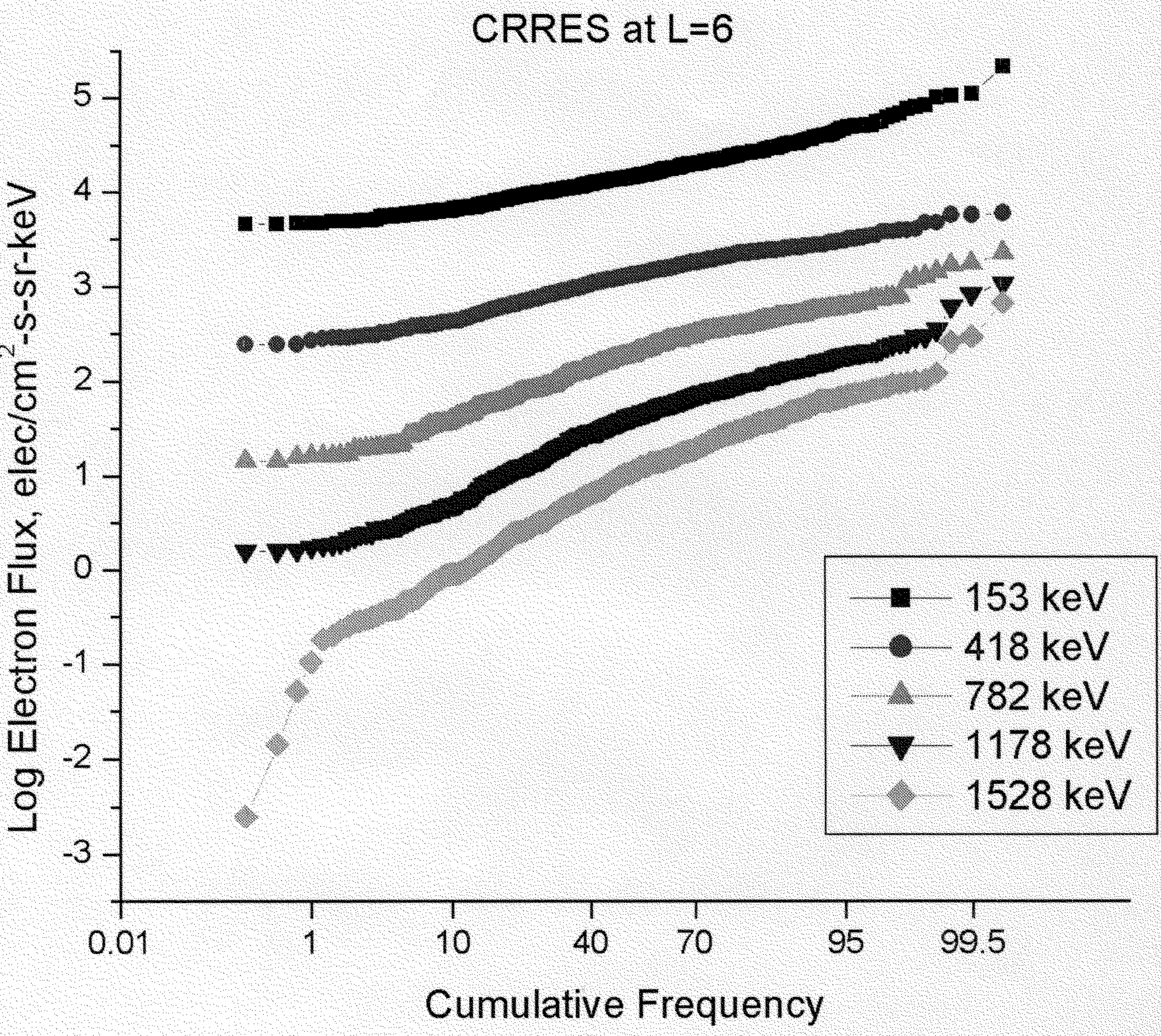
CRRES at L=3
Log Electron Flux, elec/cm^2-s-sr-keV
6
5
4
3
2
1
0
-1
1
10
40
70
95
99.5
Cumulative Frequency
153 keV
418 keV
782 keV
1178 keV
1528 keV

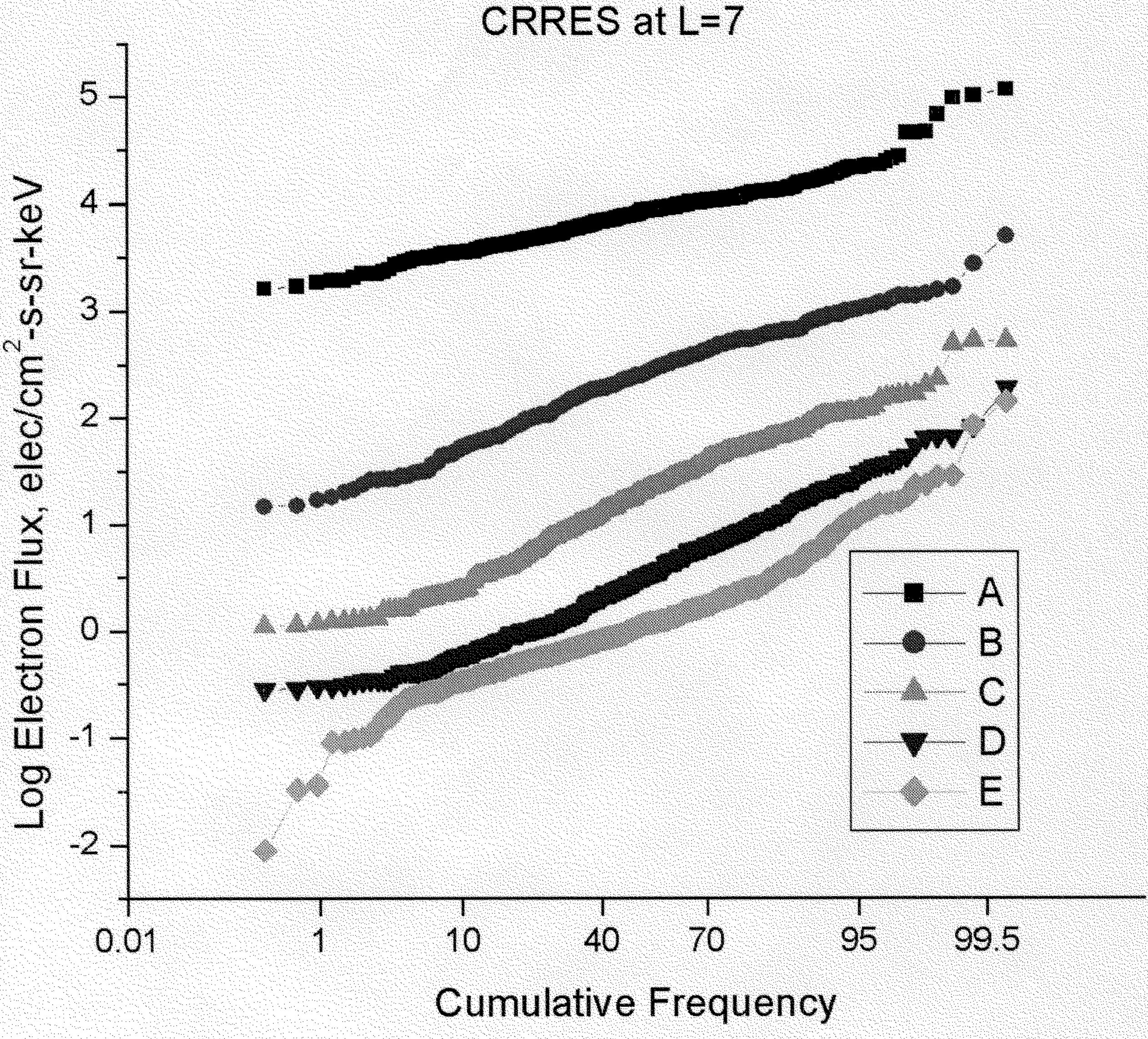


CRRES at L=4
Log Electron Flux, elec/cm^2-s-sr-keV
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.01
1
10
40
70
95
99.5
Cumulative Frequency
153 keV
418 keV
782 keV
1178 keV
1528 keV



CRRES at L=5
Log Electron Flux, elec/cm^2-s-sr-keV
5
4
3
2
1
0
-1
0.01
1
10
40
70
95
99.5
Cumulative Frequency
153 keV
418 keV
782 keV
1178 keV
1528 keV


CRRES at L=6
Log Electron Flux, elec/cm2-s-sr-keV
5
4
3
2
1
0
-1
-2
-3
0.01
1
10
40
70
95
99.5
Cumulative Frequency
153 keV
418 keV
782 keV
1178 keV
1528 keV



CRRES at L=7
Log Electron Flux, elec/cm^2-s-sr-keV
5
4
3
2
1
0
-1
-2
0.01
1
10
40
70
95
99.5
Cumulative Frequency
A
B
C
D
E

Comparison of Environment with AE8MAX

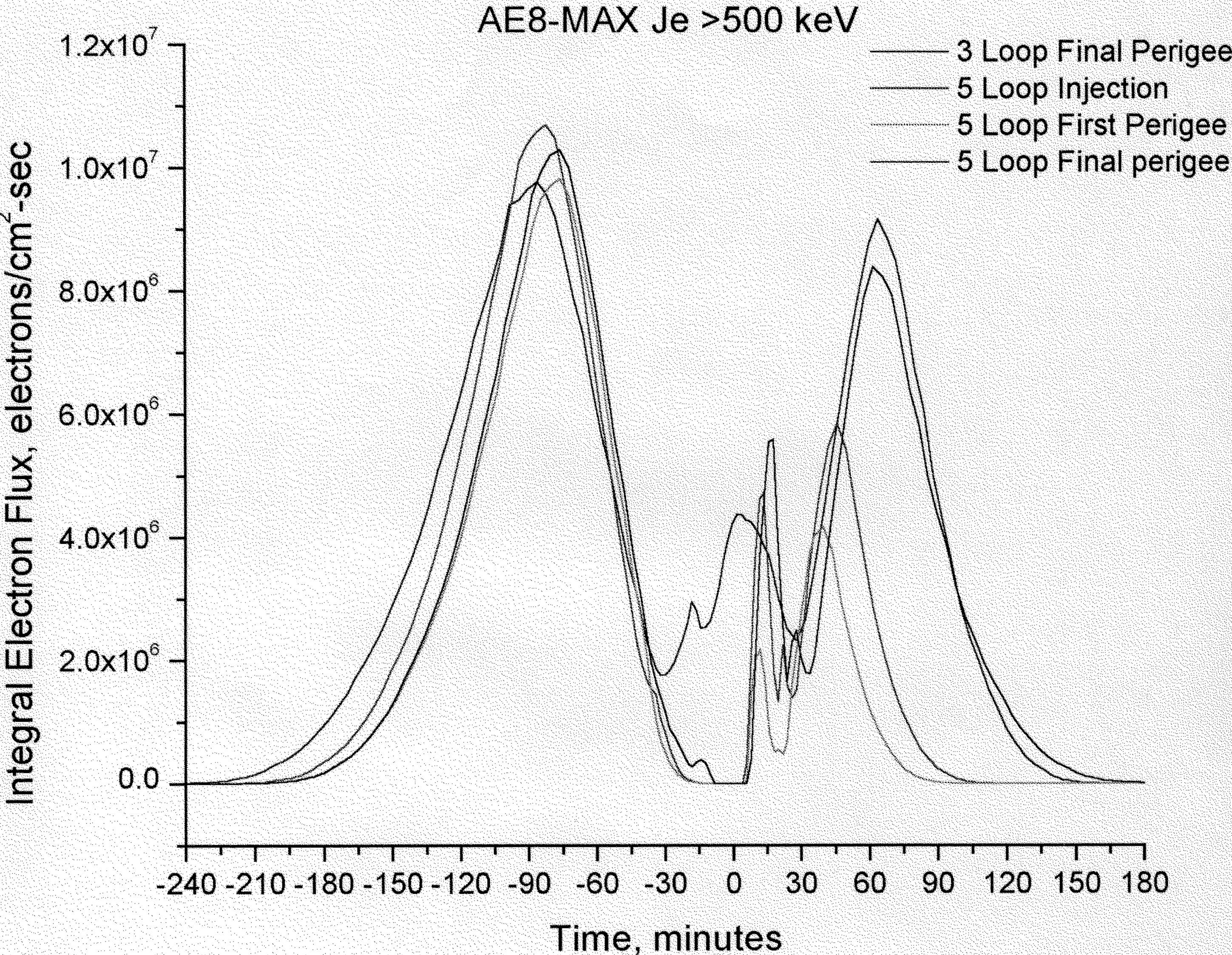
by

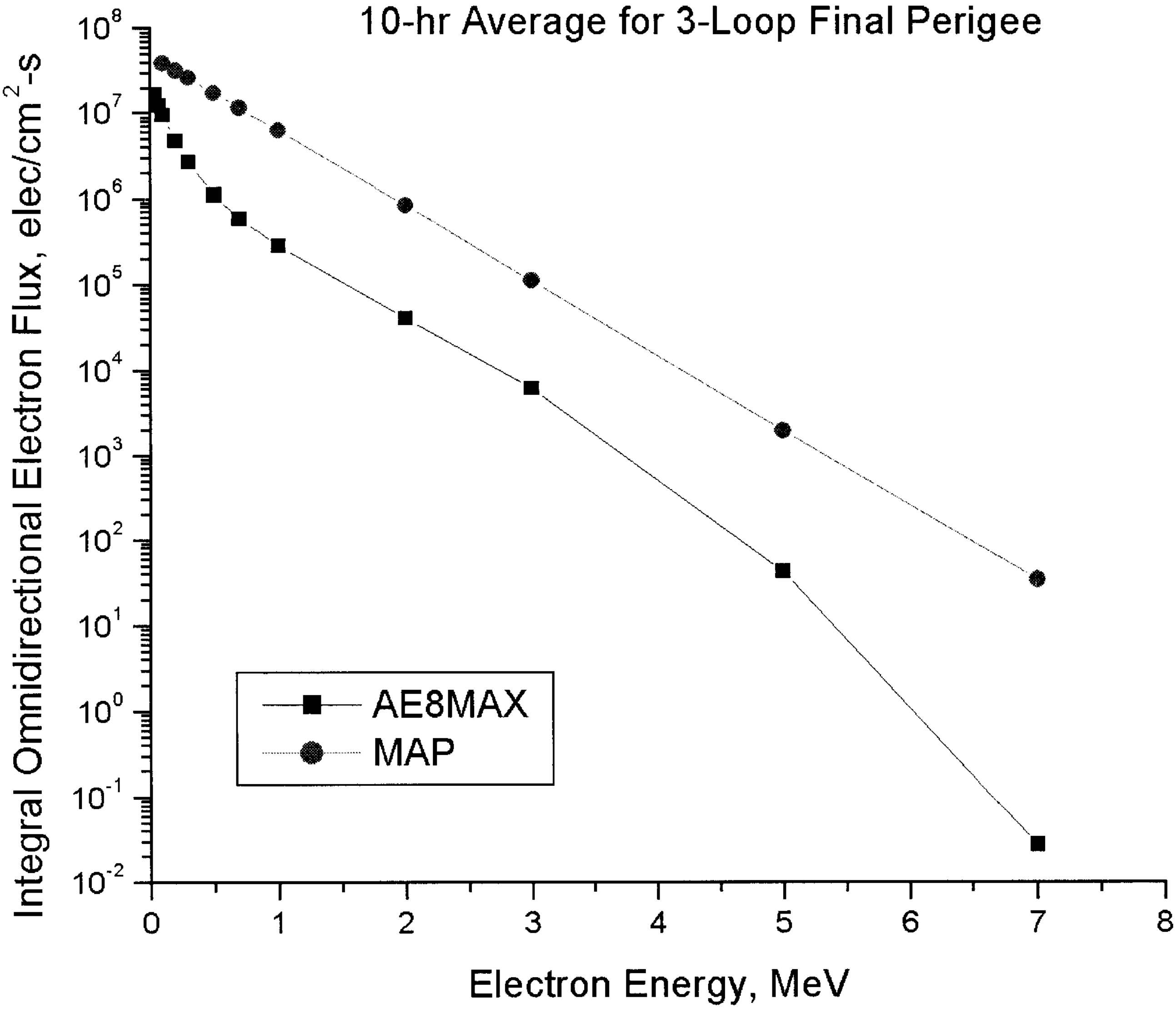
Mike Redding

Mark Looper

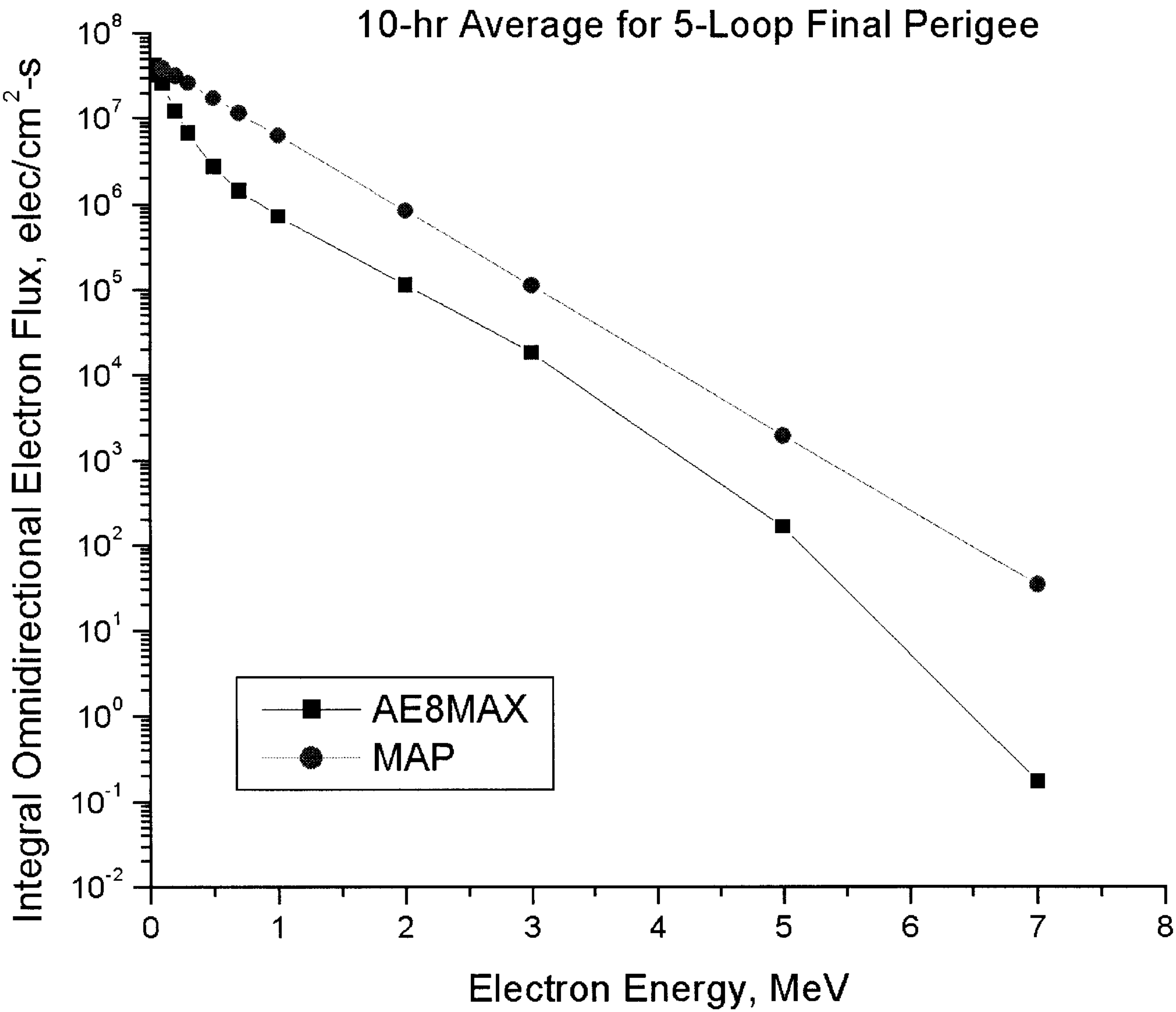
and

Harry Koons


AE8-MAX Je >500 keV
3 Loop Final Perigee
5 Loop Injection
5 Loop First Perigee
5 Loop Final perigee
Integral Electron Flux, electrons/cm^2-sec
1.2x10^7
1.0x10^7
8.0x10^6
6.0x10^6
4.0x10^6
2.0x10^6
0.0
-240 -210 -180 -150 -120 -90 -60 -30 0 30 60 90 120 150 180
Time, minutes



10-hr Average for 3-Loop Final Perigee
Integral Omnidirectional Electron Flux, elec/cm^2-s
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
0
1
2
3
4
5
6
7
8
Electron Energy, MeV
AE8MAX
MAP



10-hr Average for 5-Loop Final Perigee
Integral Omnidirectional Electron Flux, elec/cm^2-s
Electron Energy, MeV
AE8MAX
MAP
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
0
1
2
3
4
5
6
7
8

Simulation Results for Map Cable and Comparison for CRRES & MAP Cables

by

Mark Looper

and

Harry Koons

Space and Environment Technology Center

HCK 9/7/99

THE AEROSPACE CORPORATION

EGS4 (Electron-Gamma Shower) Monte Carlo Code

- Developed at Stanford Linear Accelerator Center (Nelson, Hirayama, and Rogers, SLAC Report 265, 1985)

- Electromagnetic shower radiation transport code for electrons and positrons down to 10 keV and gamma rays down to 1 keV (particles dropping below these energies are assumed to stop locally)

- Fast in-line pseudo-random number generator to sample parameter space with a Monte Carlo simulation (initial location, direction, and/or energy of incident particles, random aspects of radiation transport)

- Full physics code, with separate interaction cross sections for different materials and different processes (ionization energy loss, bremsstrahlung, delta ray generation, pair production…), *i.e.*, no need for "aluminum equivalent thickness" and similar approximations

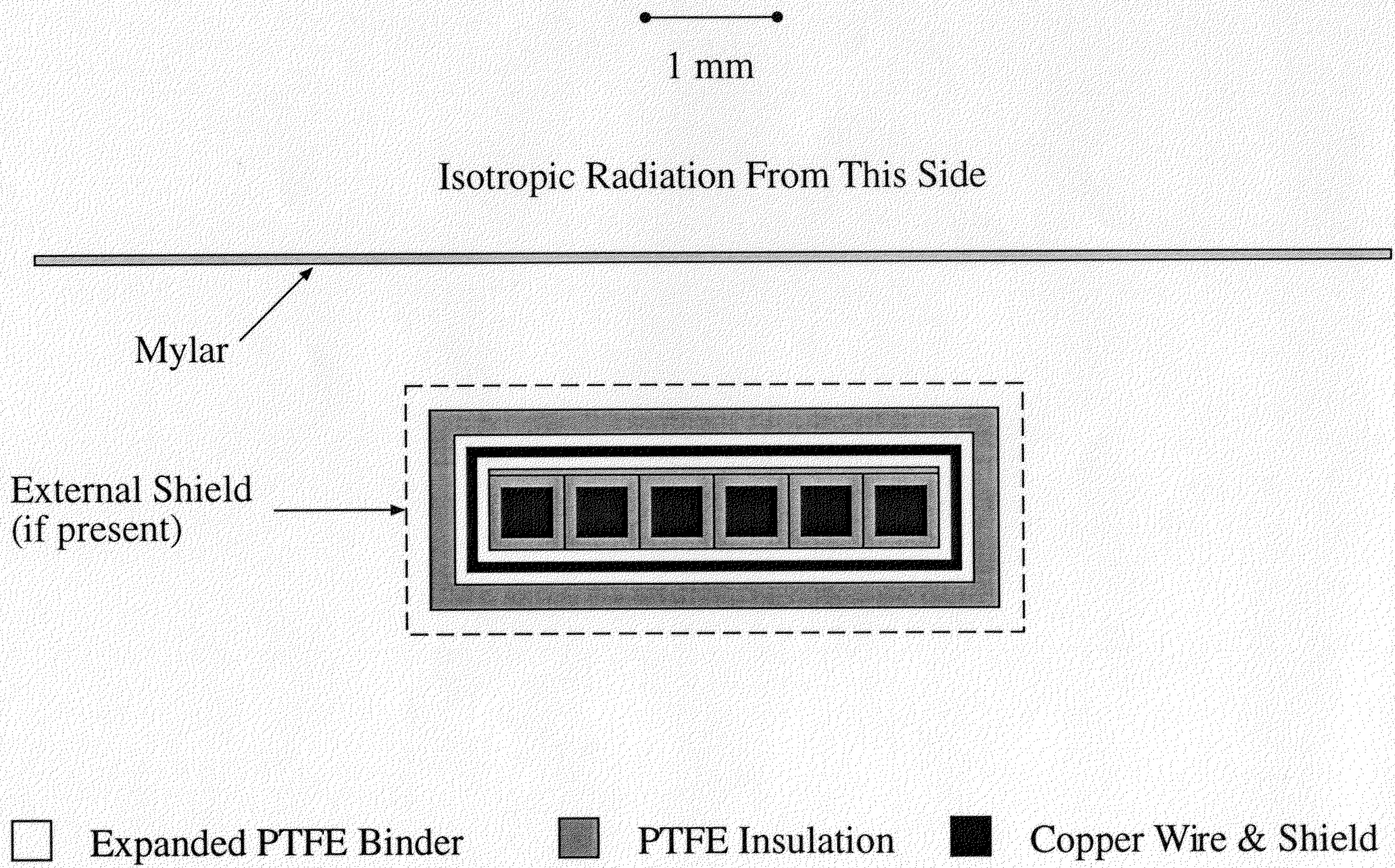
- Very flexible geometry (planes, cones, spheres, cylinders), input (different particle types, continuum spectra or monoenergetic, beam or isotropic…), and output (energy or charge deposit, path lengths, etc., particle by particle or summed over regions) under control of programmer

- Well-benchmarked code, both in the literature (references in SLAC Report 265 or on the WWW at http://ehssun.lbl.gov/egs/egs.html) and in my own work (against SHIELDOSE and against real detectors in a beta spectrometer)

- Several years of use at Aerospace, including simulations of sensors (MCP and ICO dosimeters, SAMPEX/PET, MPTB/CPT and other telescopes), test setups and instrumentation (Faraday cup, scattering foil, gamma cell), and electronics boxes in the space environment

MAP Cable Simulation Geometry

(to scale)



Simulation of Incident Electron Directions

- EGS4 provides inline code for a "uniform deviate" (pseudo-random floating-point numbers evenly distributed from zero to one) as its default random-number generator.

- For a simulated geometry like a cable that is infinite in one direction, a single sampling of a uniform deviate lets us distribute incident particles uniformly across the cable, and another sampling lets us distribute them uniformly in azimuth (projection of incidence direction into the plane of the Mylar—headed along the cable or across it?).

- In a one-dimensionally infinite geometry, the problem is "degenerate" along the length of the cable (it doesn't matter where the particle strikes in that dimension), say the y direction, so we can place all particles at y = 0 and just base normalizations on a unit length in y. In a two-dimensionally infinite geometry the need to sample in azimuth and along the other infinite dimension also disappears and we normalize to a unit area.

- In either case, we must still sample the angle of particles off normal incidence (elevation):

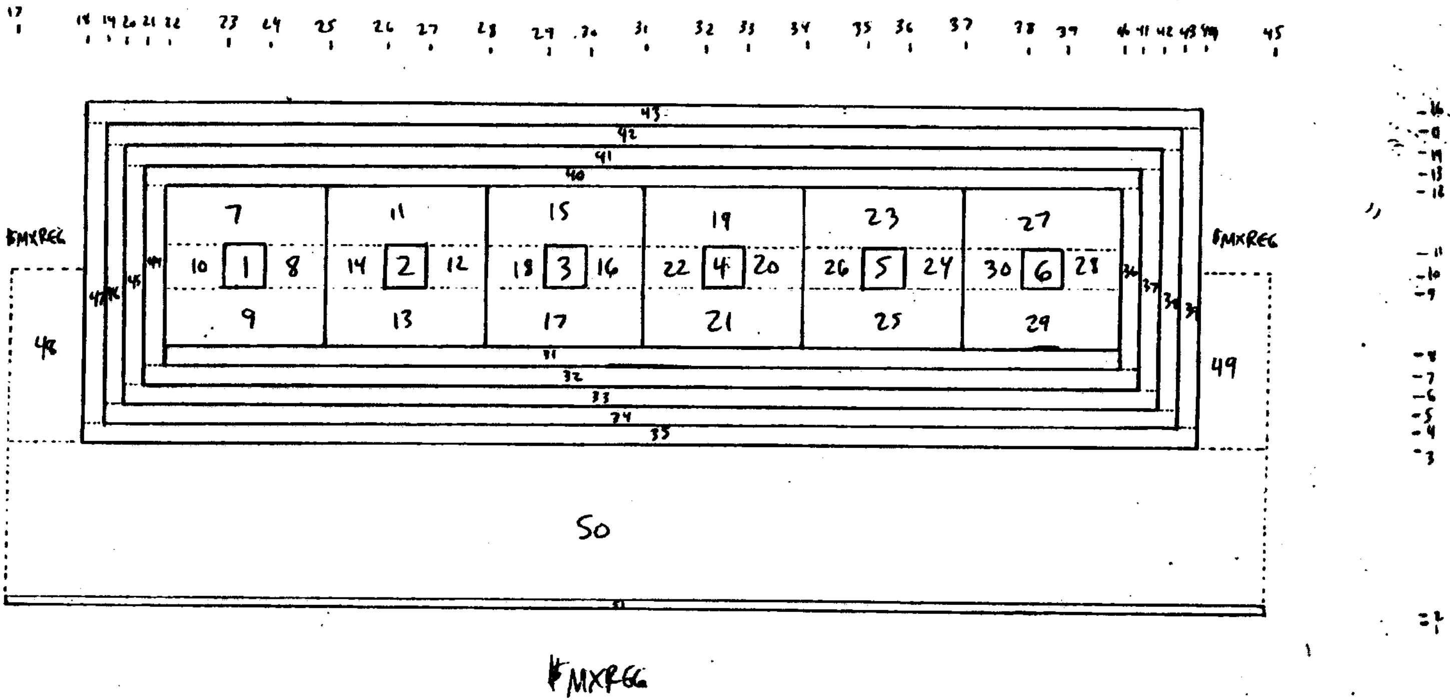
  Let θ be the angle between the cable (or rather, Mylar) normal and the particle incidence direction. Then the solid angle covered by particles within $d\theta$ of this angle is

  $d\Omega = 2\pi \sin\theta d\theta$ (this includes all azimuths), so $\int d\Omega = 4\pi$ sr for θ from zero to π.

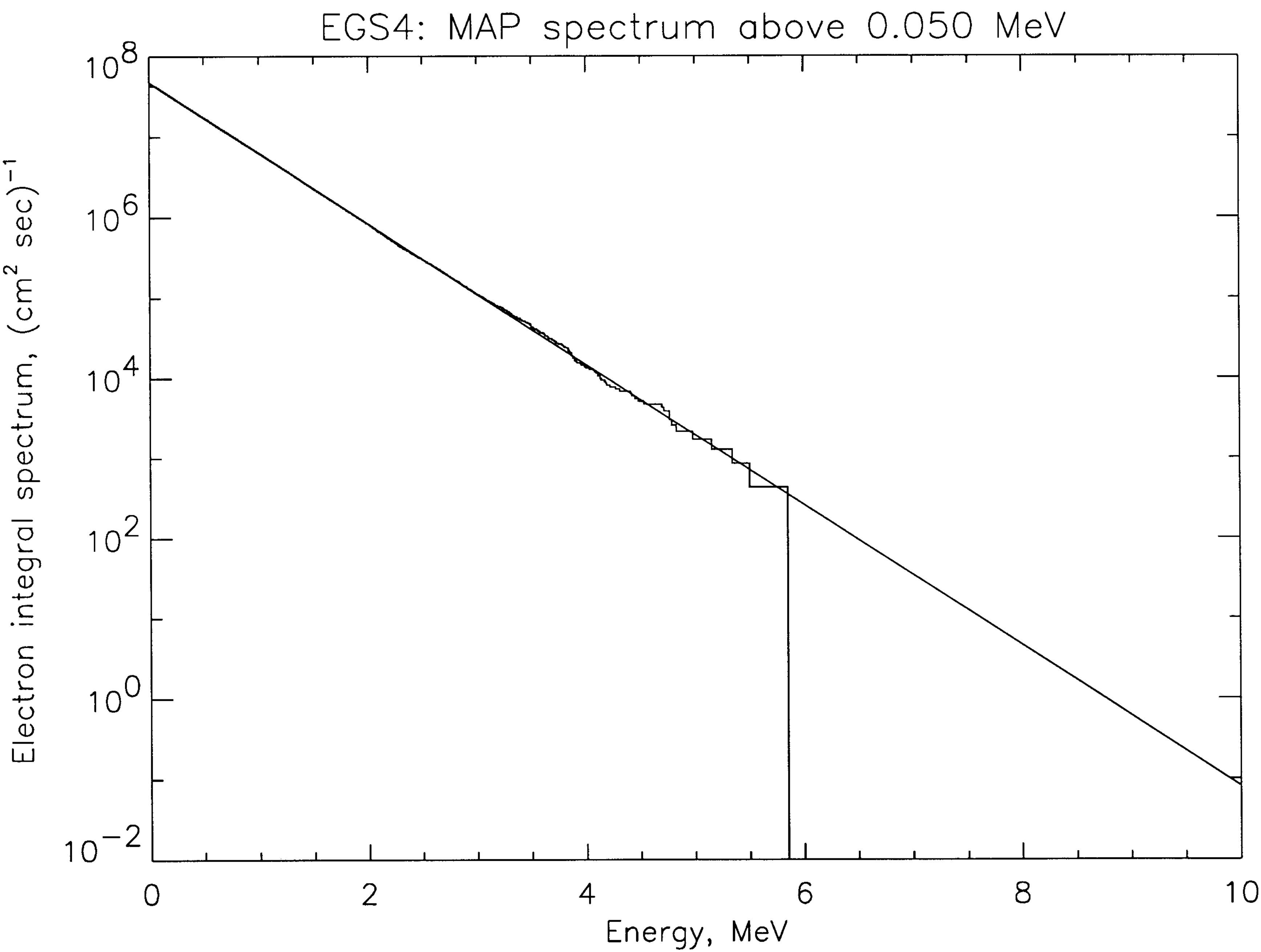
  If the radiation environment to be simulated is an omnidirectional flux of J particles per (cm^2 sec) illuminating one side of the geometry, then the directional flux is $j = J/4\pi$ particles per (cm^2 sec sr), and the number of particles per unit time striking a flat target of area A from directions within $d\theta$ of θ (which now only varies from zero to $\pi/2$) is

  $$dN = jA\cos\theta d\Omega = 2\pi jA\cos\theta\sin\theta d\theta = -\pi jAd(\cos^2\theta),\text{ so that } N = \int dN = \pi jA = JA/4.$$

  A uniform sample of N in our Monte Carlo simulation, then, is equivalent to a uniform sample of $\cos^2\theta = v_z^2$, where v_z is the normal component of the particle's unit velocity vector. This is easily done by generating a sample of the uniform deviate and assigning the square root of this as the value of v_z. Repetition of this procedure generates a representative sample of isotropically incident particles striking a flat target, *QEF*.



FMXREG
FMXREG
1
2
3
4
5
6
50
49
48
FMXREG


EGS4: MAP spectrum above 0.050 MeV
Electron integral spectrum, (cm² sec)⁻¹
Energy, MeV
10⁸
10⁶
10⁴
10²
10⁰
10⁻²
0
2
4
6
8
10

Region	Componen	(vacuum)	6 mil Cu	7.8 mil Cu	4 mil Pb
1	Wire 1	-476	-168	-115	-147
2	Wire 2	-450	-155	-114	-135
3	Wire 3	-424	-162	-113	-137
4	Wire 4	-396	-145	-107	-131
5	Wire 5	-412	-162	-119	-138
6	Wire 6	-445	-159	-118	-143
7	Insulator 1	-30	-6	-7	-7
8	Insulator 1	-41	-8	-17	-9
9	Insulator 1	-104	-29	-29	-23
10	Insulator 1	-33	-14	-13	-10
11	Insulator 2	-23	-6	-4	-11
12	Insulator 2	-45	-11	-18	-2
13	Insulator 2	-91	-43	-20	-33
14	Insulator 2	-32	-18	-13	-16
15	Insulator 3	-19	-8	-8	-10
16	Insulator 3	-29	-23	-3	-13
17	Insulator 3	-106	-42	-22	-39
18	Insulator 3	-34	-12	-2	-9
19	Insulator 4	-16	-7	-8	-3
20	Insulator 4	-46	-17	-13	-13
21	Insulator 4	-127	-32	-31	-22
22	Insulator 4	-38	-5	-12	-9
23	Insulator 5	-26	-7	-5	-1
24	Insulator 5	-46	-14	-5	-13
25	Insulator 5	-117	-42	-28	-34
26	Insulator 5	-41	-21	-12	-14
27	Insulator 6	-32	-12	-1	-11
28	Insulator 6	-49	-20	-7	-10
29	Insulator 6	-103	-43	-38	-22
30	Insulator 6	-47	-19	-11	-6
31	Carrier Insı	-352	-112	-80	-103
32	Inner Binde	-354	-112	-62	-37
33	Shield	-4635	-1063	-736	-807
34	Outer Bind	-1398	-190	-175	-184
35	Jacket	-10765	-1348	-931	-1004
36	Inner Binde	-28	-16	-15	-10
37	Shield	-378	-100	-71	-83
38	Outer Bind	-109	-34	-11	-17
39	Jacket	-706	-135	-100	-105
40	Inner Binde	-52	-24	-19	-12
41	Shield	-229	-89	-102	-90
42	Outer Bind	-38	-10	-2	-9
43	Jacket	-129	-85	-46	-80
44	Inner Binde	-34	-12	-5	-12
45	Shield	-374	-88	-67	-88
46	Outer Bind	-73	-26	-25	-22
47	Jacket	-708	-120	-83	-91
48	(buffer regi	0	0	0	0
49	(buffer regi	0	0	0	0
50	(buffer regi	0	0	0	0
51	Mylar	-12386	-13237	-13412	-13830

52	External Sl	0	-16534	-18100	-12851
53	External Sl	0	-807	-825	-576
54	External Sl	0	-105	-93	-75
55	External Sl	0	-775	-892	-646
56	(discard re	-63374	-63568	-63135	-68097
1	Wire 1	-476	-168	-115	-147
2	Wire 2	-450	-155	-114	-135
3	Wire 3	-424	-162	-113	-137
4	Wire 4	-396	-145	-107	-131
5	Wire 5	-412	-162	-119	-138
6	Wire 6	-445	-159	-118	-143
7+8+9+10	Insulator 1	-208	-57	-66	-49
11+12+13+	Insulator 2	-191	-78	-55	-62
15+16+17+	Insulator 3	-188	-85	-35	-71
19+20+21+	Insulator 4	-227	-61	-64	-47
23+24+25+	Insulator 5	-230	-84	-50	-62
27+28+29+	Insulator 6	-231	-94	-57	-49
31	Carrier Insu	-352	-112	-80	-103
32+36+40+	Inner Binde	-468	-164	-101	-71
33+37+41+	Shield	-5616	-1340	-976	-1068
34+38+42+	Outer Bind	-1618	-260	-213	-232
35+39+43+	Jacket	-12308	-1688	-1160	-1280
52+53+54+	External Sl	0	-18221	-19910	-14148
51	Mylar	-12386	-13237	-13412	-13830
1+É+56	(total cases	-100000	-100000	-100000	-100000

EGS4 Simulation of MAP Cable
Square Geometry

	No Extra Shield	7.8 mil Cu	4.0 mil Pb
Mylar	12386	13412	13830
Vacuum	63374	63135	68097
External Shield	0	18100	12851
Total Missing Cable	75760	94647	94778
Total Entering Cable	24240	5353	5222
Flux Entering Cable, elec/cm^2-sec	6.0×10^6	1.32×10^6	1.29×10^6

Example Calculation of Flux into Cable

- Number of electrons entering cable under 4 mil of Pb
  - 5222 of 10^5 electrons
- Integral omnidirectional flux above 50 keV in MAP spectrum
  - $J = 4.28 \times 10^7$ elec / cm^2 - sec
- Flux hitting 1 cm^2 area from one side
  - $J / 4 = 1.07 \times 10^7$ elec / cm^2 - sec
- Simulation area of Mylar MLI is 1.06 cm x 1 cm = 1.06 cm^2
- Simulation of 10^5 electrons striking Mylar corresponds to natural flux in
  - $(10^5 / 1.06) / 1.07 \times 10^7 = 0.0088$ sec
- Simulation area of MAP cable = 0.46 cm^2
- Flux into cable under 4 mil of Pb shielding is
  - $5222 / (0.46 \times 0.0088) = 1.29 \times 10^6$ elec / cm^2 -sec

Material Properties

Material	Density, g/cm^3	Z, Atomic Number
Al	2.70	13
Cu	8.93	29
Pb	11.3	82

EGS4 Simulation of Flat MAP Cable

External shield	(none)	6 mil Cu	7.8 mil Cu	4 mil Pb
(backscattered)	-24261	-32461	-32566	-41624
Mylar	-15021	-17019	-17425	-18390
External shield	0	-37921	-40815	-30281
Jacket	-27961	-3299	-2326	-2350
Binder	-3877	-662	-466	-449
Internal shield	-13270	-3040	-2148	-2259
Binder	-1032	-290	-219	-214
Carrier insulation	-1277	-366	-273	-328
Insulator	-2366	-780	-535	-572
Wire	-10022	-3734	-2892	-3145
Insulator	-72	-44	-22	-38
Binder	-37	-24	-11	-19
Internal shield	-145	-64	-75	-72
Binder	-28	-14	-10	-18
Jacket	-43	-54	-41	-55
External shield	0	-72	-74	-49
(penetrating)	-588	-156	-102	-137

EGS4 Simulation of Flat RG316 Cable with 0.02 cm (CRRES IDM Shielding)

(backscattered)	-28965
0.02 cm Al	-36827
Jacket	-16377
Shield	-14219
Insulator	-1732
Steel wire	-1643
Insulator	-86
Shield	-88
Jacket	-4
(penetrating)	-59

Recommendations

- Shield cable with 4 mils of Pb tape behind 3 mils Mylar MLI
  - Justification
    - Best shielding per unit of added weight
      - 4 mils of Pb is 0.65 the weight of 7.8 mils of Cu but shielding is essentially identical
    - Shielded cables on CRRES with less environmental shielding survived over 800 orbits with no discharges.
    - Worst-case flux to MAP cable is 2.6 times "Zero Discharge Level" for all IDM samples on CRRES
      - Zero Discharge Level included many FR4 Epoxy Fiberglass Boards that had a large number (> 1000) ESDs during the CRRES mission.
- Perform MIL-STD-1541A Arc Discharge Test or equivalent at system level to verify circuit immunity